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OIL SPILL DRIFT CAUSED BY THE COUPLED EFFECTS OF WIND AND WAVES

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16. Abstract

A one year study of the potential effect of wind and waves on oil spill drfit was completed in the Engineering Research Laboratories at the University of Missouri - Rolla. The investigation was initiated to evaluate the importance of coupled wind and wave drift mechanisms for computer simulations of the total drift. The general approach in the past has been to neglect any drift effects caused by waves. The results in this investigation show that wave effects are coupled to wind effects in a complicated manner and neglecting the waves can lead to serious errors.

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FOREWARD

This report presents the results of an experimental study of the effects of wind coupled with waves on the movement of oil on a water surface. The University of Missouri - Rolla conducted this study for the U. S. Coast Guard under contract DOT-CG-24603-A. Dr. Saul Broida was the technical monitor for this contract.

D. J. Alofs, R. C. Shah and S. K. Banerjee contributed significantly to this program and their efforts are hereby acknowledged.

SUMMARY

A one year study of the potential effect of wind and waves on oil spill drift was completed in the Engineering Research Laboratories at the University of Missouri - Rolla. The investigation was initiated to evaluate the importance of coupled wind and wave drift mechanisms for computer simulations of the total drift. The general approach in the past has been to neglect any drift effects caused by waves. The results of this investigation show that wave effects are coupled to wind effects in a complicated manner and neglecting the waves can lead to serious errors.

The experiment was designed to allow the waves to be generated independently from the wind. Drift velocity results for oil lenses and other floats are reported for wind currents and water waves traveling in the same direction, in the opposite direction and at fixed angles to each other.

Experimental results are presented for a free stream wind velocity from zero to 700 cm/sec; the wave steepness ranged from zero to 0.069, which is near the maximum steepness for stable laboratory produced gravity waves. This represents the entire range of possible wave steepness, and probably the range of possible wind speeds which can practically by studied in the laboratory. The results show that the wind drift and wave drift mechanisms are not simply additive or subtractive over all regimes of wind speed. At low wind speeds the wave drift is shown to provide an augmentation to the wind drift. However, at higher wind speeds, the waves cause a net decrease in the coupled drift velocity. In

fact, this wave induced diminishment increases as the wind speed increases.

Experimental results are also reported for the effects of wave length, air turbulence and float design.

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INTRODUCTION

The responsibility of The United States Coast Guard to enforce antioil pollution statutes is outlined by Lehr [1]. Lehr summarizes the Coast Guard's research and development projects and funding levels in oil pollution abatement. Past and current efforts are reported to be centered on developing seagoing systems to reduce oil quantities released during tankship accidents, contain the spread of spilled oil in thick films to facilitate recovery operations, and harvest spilled oil from the ocean surface.

A capacity to predict accurately the path of an oil spill can facilitate the effective mobilization of available cleanup resources and provide a tool for law enforcement. The simple oil path model reported by Smith [2] for the Torrey Canyon accident clearly shows the feasability of creating a computational scheme to aid in the tracking and surveillance of oil spills. A scheme useful for tracking an oil spill would involve a computer-prepared map which would depict such items as geographic coordinates, oil velocities, and times into the future. This information could be used to deploy cleanup equipment to a predicted rendezvous point where harvesting of the oil would take place. With financial responsibility also an issue, the possession of evidence would help assign blame in the event that no one admits to having spilled the oil. In this case the computerized tracking scheme would be used to predict the path of the oil backward in time to determine the most probable source of the spill.

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*Bracketed numbers refer to the bibliography.

The creation of a computer oriented, tracking, predictive technique requires an accurate understanding of the physical mechanism which causes movement of an oil spill. It is also important to understand how these drift mechanisms interact to cause a net movement of an oil spill. Wind and waves produces drift and in many cases represent the major and most variable effects which must be considered. The question as to whether wave effects can be neglected in a total drift simulation formed the basis for this study.

On the ocean, wind, waves and currents can all cause the center of an oil spill to move with respect to the oil source. As reported by Smith [2], the wind is the major factor causing oil spill movement. However, the wind causes waves as well as surface drift. At any instant of time, the wind direction may not coincide with the wave direction. Thus, an accurate predictive scheme for oil spill movement must take into account both wind and wave drift mechanisms.

Attention was focused on the oil spill problem when the tanker, Torrey Canyon, went aground off the coast of England, spilling almost thirty million gallons of oil. It was estimated that the Torrey Canyon spill cost the British government eight million dollars, but the cost to the society was even greater due to the loss of a valuable energy resource as well as damage to water birds, fish, and the beaches. A factor which is often overlooked is the fact that the earth's natural reservoirs contain a limited amount of oil. It is just as much of a disaster to lose this source of energy as it is to let the spill hit land and pollute the beaches and wildlife. Harvesting the oil from the ocean surface is desirable and possible.

Once an oil spill has occurred, it is imperative that cleanup operations be immediately undertaken to minimize damage. The ability to predict the path of an oil slick would be of great value for two reasons. First, predicting the path that an oil slick will follow is a necessary step in the mobilization of cleanup resources. Second, if the origin of an oil spill could be accurately determined, the party responsible could be required to pay for the damage and cleanup costs. If local surface wind were the only factor determining the drift speed and direction of oil, computing the location of a spill at a certain time would be easy. But different winds, miles from the spill, can affect the local wave system. This complicated interaction between wind and waves was evaluated and the significance of waves is reported.

Previously, laboratory experiments were conducted by Alofs and Reisbig[3] in which the single effect of waves on surface drift was studied and compared to the results to the Stokes[4] wave theory. The measured velocities of floats were in all cases greater than the surface drift predicted by the Stokes theory. For wave conditions at which the Stokes velocity was higher than 2 centimeters per second, the measured velocities of the surface floats were 35 to 150 percent greater than the Stokes velocity. These experiments also indicated that a float's velocity is independent of the float material as long as it does not penetrate too deeply into the water.

The results of various studies have been used to estimate the surface drift in the ocean. The surface drift was reported by Smith[2] to be in the

direction of the wind and 3.3 percent of its velocity. Field experiments were conducted by Tomczak [5] to check the relation between the wind velocity at 10 m above the sea and the velocity of the respective surface drift current. Post cards wrapped in water-tight plastic envelopes were used as drift bodies. It was reported that the average velocity of the surface layer was 4.2 percent of the wind velocity. Schwartzberg [6] reports that the oil, on the average, drifted downwind at a speed equal to 3.09 percent of the wind speed. Van Dorn [7] and Keulegan [8] both reported that the surface moves with a velocity about 1/30 that of the wind velocity. Vines [9] and McArthur [10] separately measured the ratio of drift velocity to wind velocity by observing the drift of monomolecular films spread on the exposed surfaces of lakes. Vine's results agreed with Keulegan and Van Dorn while McArthur obtained values between 4 and 7 percent of the wind velocity. Fitzgerald [11] studies the effect of wind velocity on surface drift velocity for both smooth and wavy water surfaces. His laboratory experiments showed that the surface drift velocity was markedly affected by the damping of surface waves. For a wavy surface with clean water the drift was a constant 3.0 percent of the air velocity. Surface waves were damped by the addition of a detergent to the water. For a detergent contaminated surface the drift velocity approaches a maximum value of 4.5 percent of the wind velocity for wind speeds greater than 550 centimeters per second. It is interesting to note that the range of variation in drift velocity outlined above is rationalized by the coupled effects of wind and waves. This fact is discussed in detail.

DISCUSSION OF WIND-WAVE INTERACTION (THEORY AND EXPERIMENT)

The interaction of wind with waves has received significant attention in the literature, however, recent reports seem to project several new questions. Much of the confusion centers around the structure and mechanism of turbulent flow. Since turbulent flow is an integral part of wind-wave interaction, it is little wonder that one finds so many theories in the literature. The observations now available indicate that the momentum transfer across the air-sea boundary is a result of a complicated interplay between the sea state, the wind and the air density or temperature. The history of flow variables at points upstream of a fixed sampling site may also be important. These factors have induced Hidy [12] to report that any future measurements of momentum transfer will be of little use in advancing our understanding of the vertical fluxes without simultaneous detailed measurements of the wave structure, as well as the thermal stratification of both the air and perhaps the surface liquid layers of the ocean. Monin [13] indicates that there is presently a poor understanding of the mechanism by which momentum and kinetic energy is transmitted and divided between waves and drift currents. He notes that the usual practice of ignoring the fact that the momemtum flux is divided between waves and surface drift is without foundation. The presence of drift currents at the air-sea boundary complicated the problem since the momentum flux undergoes a discontinuity.

A short review of some of the more widely discussed wind-wave theories may be instructive at this point. It is important to note that each theory has added substantially to the understanding of what is a most complicated phenomena.

Some of the earlier theories of Jeffreys, Phillips, Sverdrup and Munk are discussed by King [14]. The Phillips' [15,16] model and its various updatings has received considerable attention in the literature. Phillips' theory is based on a turbulence ' 'anism in which a wave resonance is set up in a random field wave pattern. The turbulent nature of the wind is an essential factor in the growth of waves and causes random stresses on the water surface. Miles [17,18,19] has provided a theory on the generation of surface waves caused by turbulent shear flows at the air-water surface. Miles, like Phillips, has presented a number of updatings to his theory. The Miles' model accounts for the air-sea coupling which causes an interaction of excitation and response between the wind and the waves which was not included in the Phillips' resonance theory. Miles later modified his theory by incorporating the Phillips' model, suggesting that both mechanisms must be operative to some extent in nature. This point of view has been supported in recent papers by Bunting [20], Barnett [21] and Davies [22]. Schwartz [23] reports that based on an experimental photographic analysis of the onset and growth of capillary-gravity waves, the theory of Phillips gave a reasonable correlation to the data. Hess [24] observes that the mechanism of air-sea interaction is only partially understood as a result of a lack of observed data for testing modern dynamical theories. He gave some credit to the older ideas of Rayleigh [25] but seemed to favor the ideas of Phillips. Chang et al. [26], reports a very clever experimental laboratory study of the structure of turbulent air immediately above and between the crests of water waves. They

report that their results support the separation mechanism of energy transfer originally outlined by Jeffreys [14].

Much of the effort in the papers mentioned above was devoted to the formation and growth of waves caused by wind. As was indicated, much can be learned about the energy transfer mechanisms even though the conditions are transient during the growth phase of wave formation. The problem of greater interest in the present study concerns the interaction in which the wind and waves are not related to each other. In this case the surface drift is affected by the fact that the wind and waves are not from the same sources. To produce this condition the waves should be generated independently of the wind. Lai and Shemdin [27] used this approach in a recent laboratory investigation of air turbulence above simple water waves. Shemdin [28] recently finished experiments in which the conditions in the air, the drift at the air-water interface and the flow profiles in the water were studied. Unfortunately, this study can not be compared with the results being reported since the drift measurements seem to be taken only with waves absent. For cases where wind and waves acted together, only the change in the wave phase speed is reported.

Recent field studies are adding needed data about the conditions at the air-sea interface. The recent BOMEX project reported by Pond et al. [29], contains this type of data and outlines the problems associated with field experiments. The field experiments reported by Smith [30] indicate that the interface drag coefficient was constant over a range of wind speeds from 7 to 16 m/sec.

The field results of Zubkovski and Kravchenko [31] indicate that the drag coefficient increases as the wind velocity gets larger. This apparent contradiction may have been the result of a different set of air-sea conditions during the experiments. A possible example is the interesting field observation made by Fleagle [32] about the effect of air temperature on wave heights. He observed that significantly higher waves are generated in cold air than in warm air. This indicates that the sea state conditions may be significantly different when the water is either colder or warmer than the atmosphere. A systematic laboratory evaluation of Fleagle's observations seems in order to uncover yet another variable which may have been overlooked in past evaluations.

DESCRIPTION OF THE EXPERIMENT

Since winds of significant velocity always tend to produce waves, it is rather difficult to isolate the direct wind effect from the indirect wind effect; that is, the wave effect. It is, however, possible to generate waves by mechanical means, rather than by the wind, so that the affect of waves on oil drift can be isolated or coupled in the laboratory to the drift effect caused by wind. The following experimental program was, therefore, initiated.

The experiments were conducted in a wind-wave tank (Figure 1). The tank was equipped with a mechanical wave generator at one end and a sloping beach at the other. The wave tank was 9.75 m long, 1.00 m wide and 0.61 m deep. A wind tunnel was fixed to the top of the tank to generate a controlled air flow in the test section above the water (Figure 2). The water level in the tank

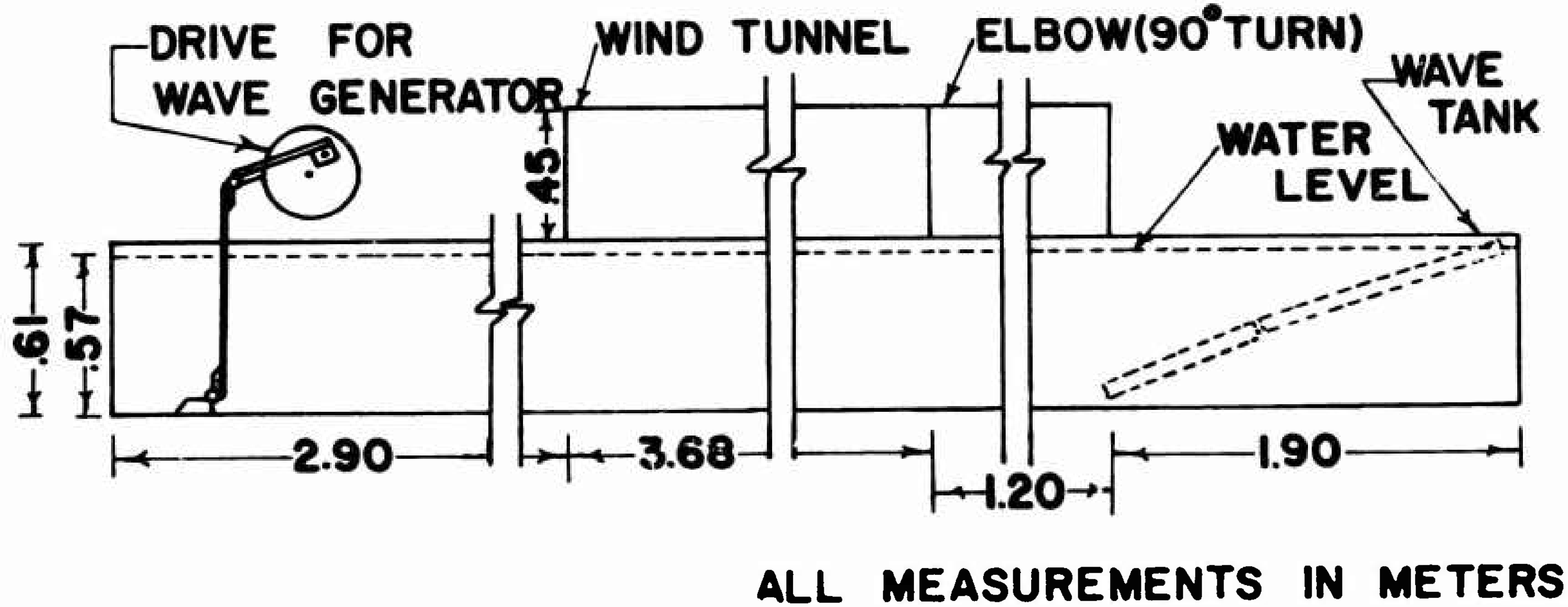

Figure 1. Schematic of the wind-wave device.

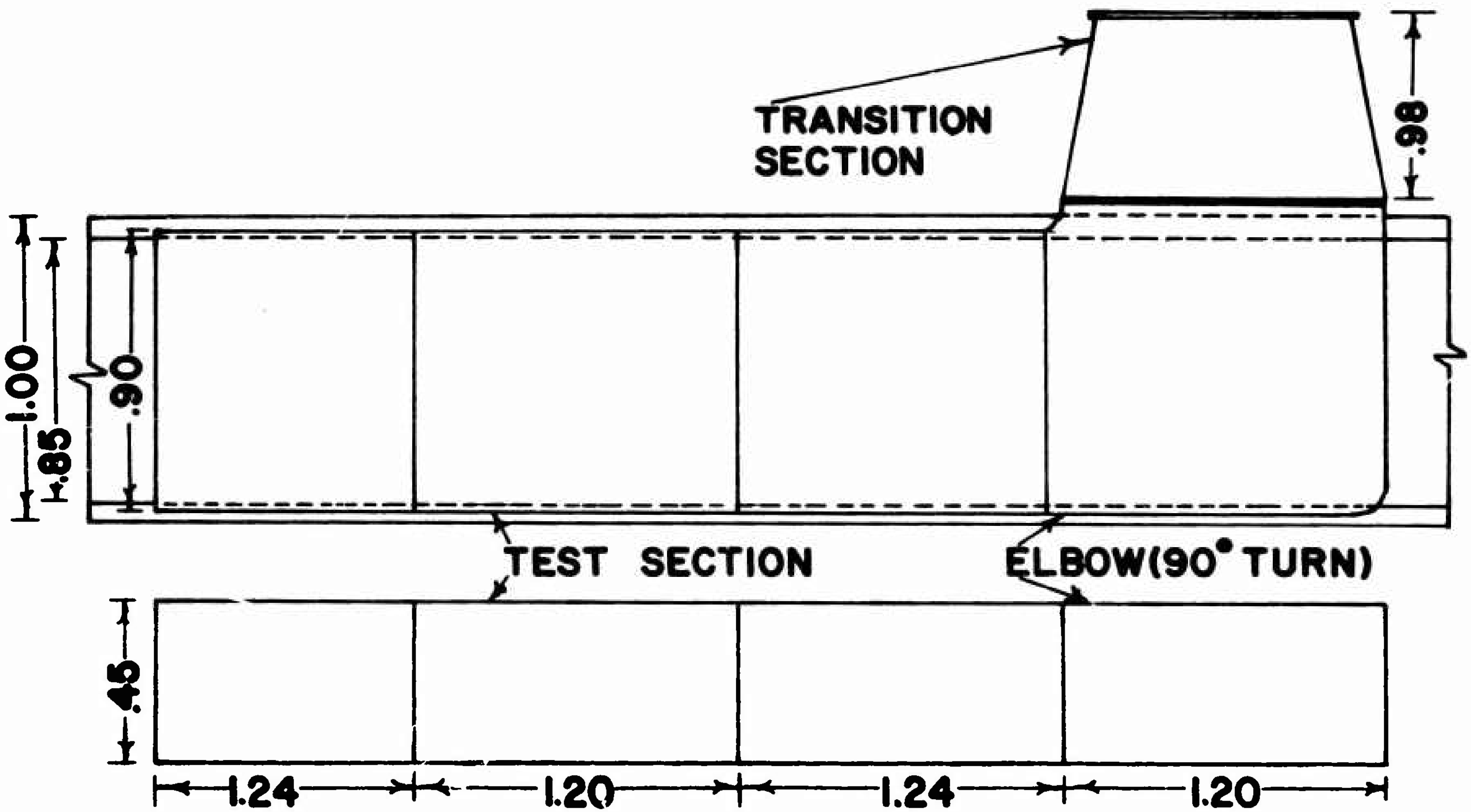

Figure 2. Schematic of the wind tunnel.

was always maintained at 0.56 m throughout this series of experiments. Both the tank and the wind tunnel were equipped with glass sections to allow conditions in the test section to be viewed. The inside dimensions of the wind tunnel measured 0.45 m high and 0.85 m wide. The test section of the tank was 1.2 m long and located 3.79 m from the wave generator. The test section was located 1.24 m from the entrance of the wind tunnel. This design insured that the air velocity profile would not be fully developed in the test section. This produced a constant pressure condition through the test section and outside the air-water interface boundary layer. Various screens and flow straighteners were placed over the entrance of the wind tunnel to control turbulence levels and to create uniform velocity profiles.

Oil slicks were made by placing a given amount of paraffin of oil onto the water surface. This oil does not continuously spread on water but rather forms a lens of stable diameter. In addition to oil floats, thin flexible plastic floats were used. The plastic float material consisted of two sheets of plastic which were bonded together forming a quilted pattern. The air cells formed were 0.7 cm on a side and 0.015 cm thick. All floats were circular with a diamter of 38.1 cm. Alofs and Reisbig [2] reported in a previous study that the float dimensions must be greater than the length of the water waves to avoid drift variations caused by surface motions in the wave. The net effect is an integrated drift effect which remains constant for any multiple of wave lengths. It was also reported that oil and plastic floats of comparable size produced the same

wave induced drift velocities. A series of tests were initiated to see if oil and plastic floats behaved the same when subjected to wind induced drift. It was found that the wind induced drift velocity was the same for both oil and plastic floats. This result justified the use of the quilted plastic floats which were much easier to handle and they did not cause contamination of the water surface as did the oil floats. It should be noted that substantial effort was made to maintain a clean air-water interface. Water surface contamination can cause undesirable variation in the experimental results.

A centrifugal fan was used to pull the air through the test section. Air flow was controlled by opening or closing a shutter on the discharge side of the fan. A Disa type 55D01 universal constant temperature anemometer and hot-film probe type 55A80 were used to measure air velocity and turbulence. The probe was designed to be indexed horizontally and vertically throughout the entire cross-section of the wind tunnel.

The following experimental procedure was used. The water in the tank was allowed to become quiescent. A float was then laid upon the water surface about 30 cm upstream of the wind tunnel entrance. The wind device and wave generator were started causing the float to move into the wind tunnel. The time required for the float to travel through the 1.20 m test section was then measured. This measurement completed the data run. After each data run the system was again allowed to become quiescent. To establish a data point, several data runs were made and used to give an average value for each set of conditions. In each data run, the system was in operation for less than five minutes. This procedure

was developed and reported by Alofs and Reisbig [2] to minimize the effect of the backflow currents which are characteristic of wave tank experiments. Further details about the experiment are presented in Appendix 3.

EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results will be segmented and discussed in three separate sections. Each section represents a specific set of experiments which includes the cases; a) the wind and waves move in the same direction, b) the wind and waves move in the opposite direction, c) the wind and waves move at fixed angles to each other.

The Case of Wind and Waves Traveling in the Same Direction

The results of the surface drift velocity experiments on the coupled parallel effects of wind and waves moving in the same direction are shown in Figure 3. Experimental results are presented for a free stream wind velocity ($\bar{V}$) from zero to 700 cm/sec; the wave steepness ranged from zero to 0.069, which is near the maximum steepness for stable laboratory produced gravity waves. Thus, Figure 3 contains the entire range of possible wave steepness, and probably the entire range of wind speeds which can practically be studied.

It can be seen from Figure 3 that wind drift and wave drift mechanisms are not directly additive over all regimes of wind speed. At low wind speeds (say below 80 cm/sec) the wave drift is shown to provide an augmen ation to the wind drift. However, at higher wind speeds the waves cause a net decrease in the coupled drift velocity. In fact, this wave induced diminishment increases as the wind speed increases.

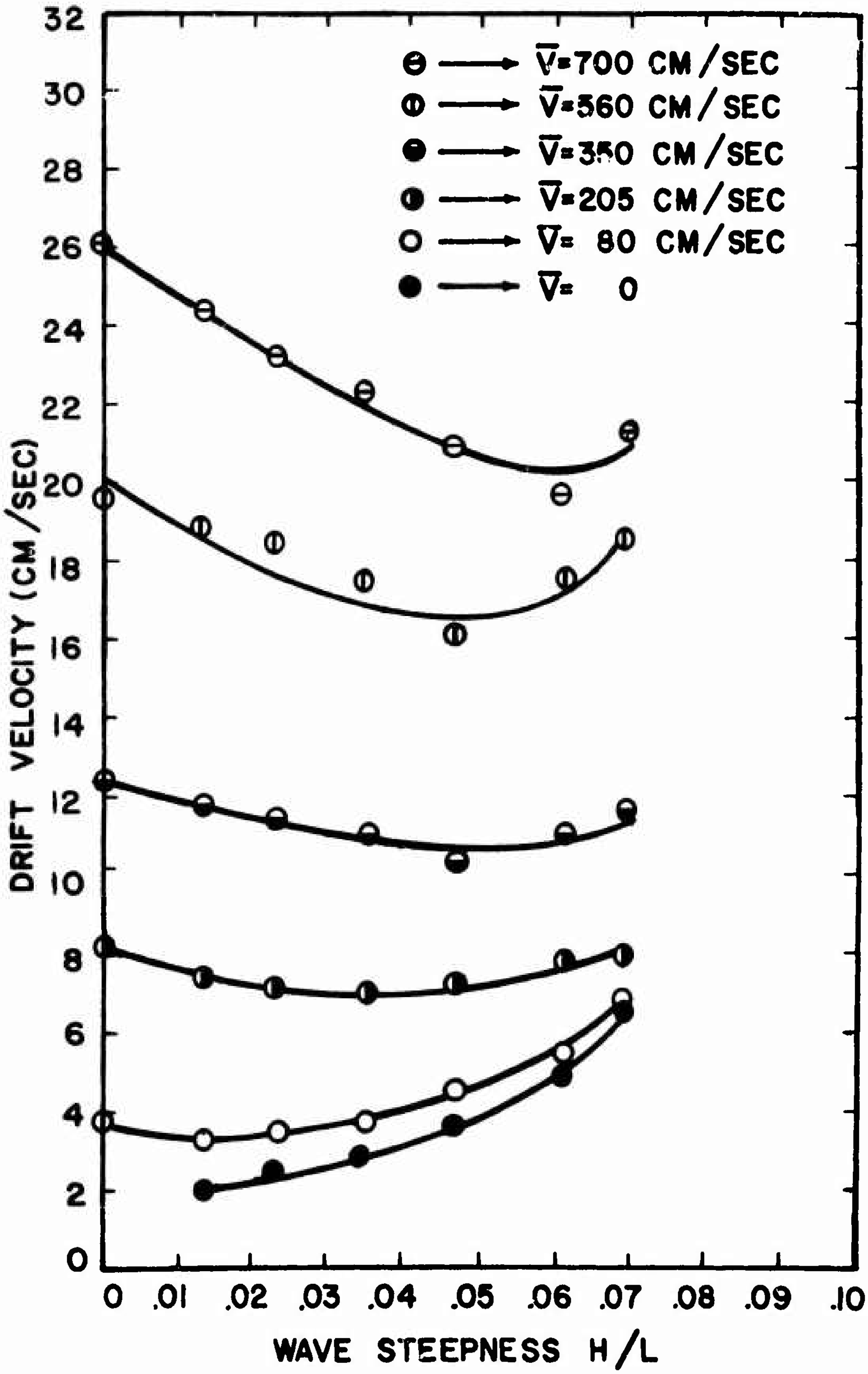

Figure 3. The effect of wave steepness on drift velocity

The depressive effect of waves on the coupled drift velocity is believed to be caused by a complicated air vortex flow in the troughs of the waves. An understanding of this mechanism is prerequisite to an accurate drift prediction capacity. It is evident that the wave effect may often be smaller than the wind effect; however, the wave effect is not negligible. Figures 4 and 5 present the same data as Figure 2 and give emphasis to the effect of wind speed on the coupled drift velocity. In the field studies mentioned in the introduction, the drift velocity was reported as a percentage of the local wind velocity. The data shown in Figure 3 ranges from 2.86% to 4.75% of the wind velocity. It is interesting to note that this range is similar to the results reported for the various field observations.

Figure 6 represents the results of an experiment to determine the effect of wave length on the coupled wind and wave drift velocity. A 31% increase in wave length produced less than a 2% increase in the coupled drift velocity. Since the increase is within the range of experimental data scatter, it is concluded that the wave length range investigated for this study had a minimal effect on the surface drift.

Figure 7 shows the results of an experiment to determine the effect of air turbulence on the drift velocity. As reported above, there have been a number of recent theoretical papers that raise questions about the importance of turbulence and its affect on the momentum tra. .er between wind and waves. It is not known whether the energy associated with increased turbulent momentum

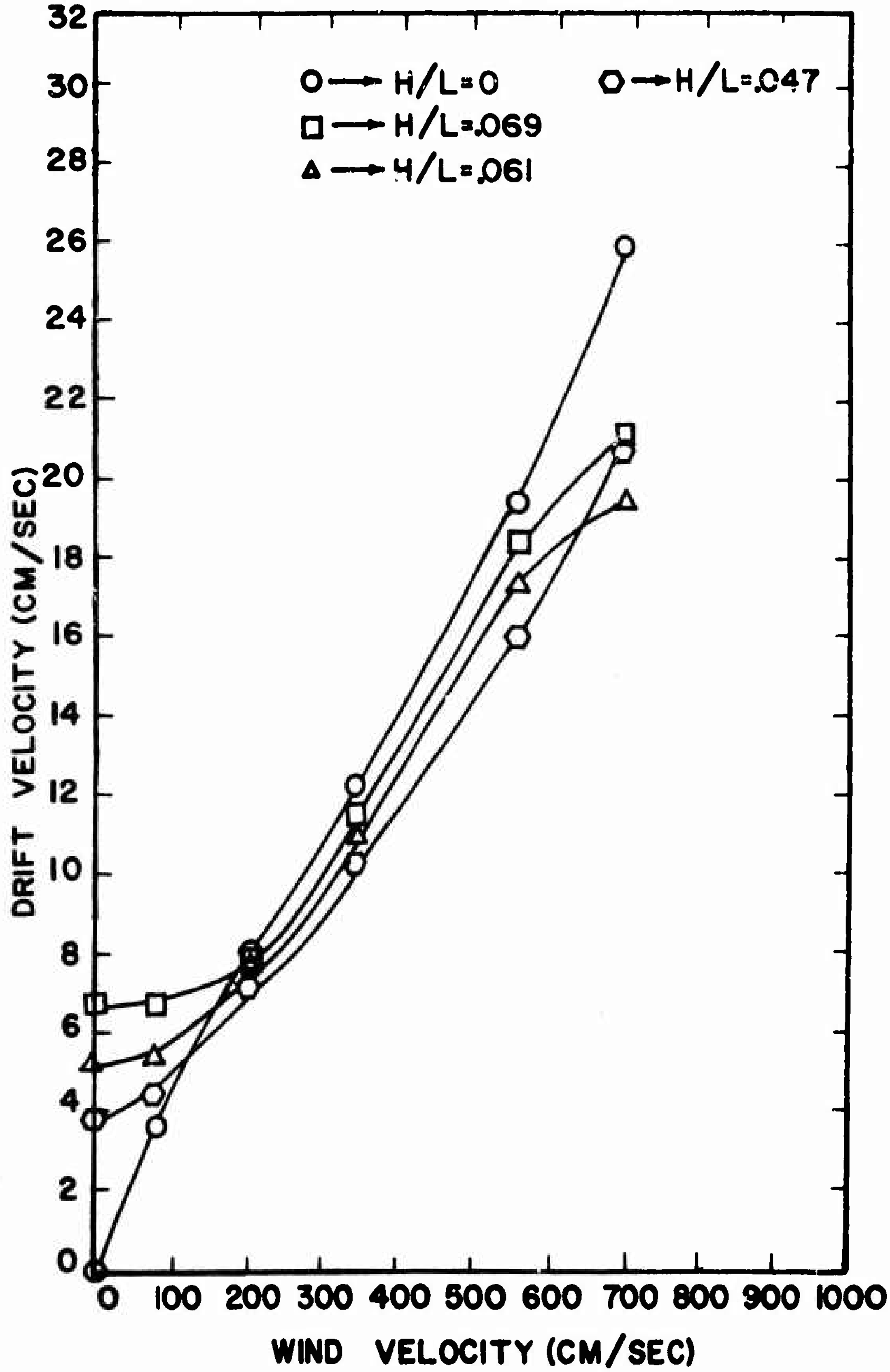

Figure 4. The effect of wave steepness and wind velocity on drift velocity (moderate to high H/L)

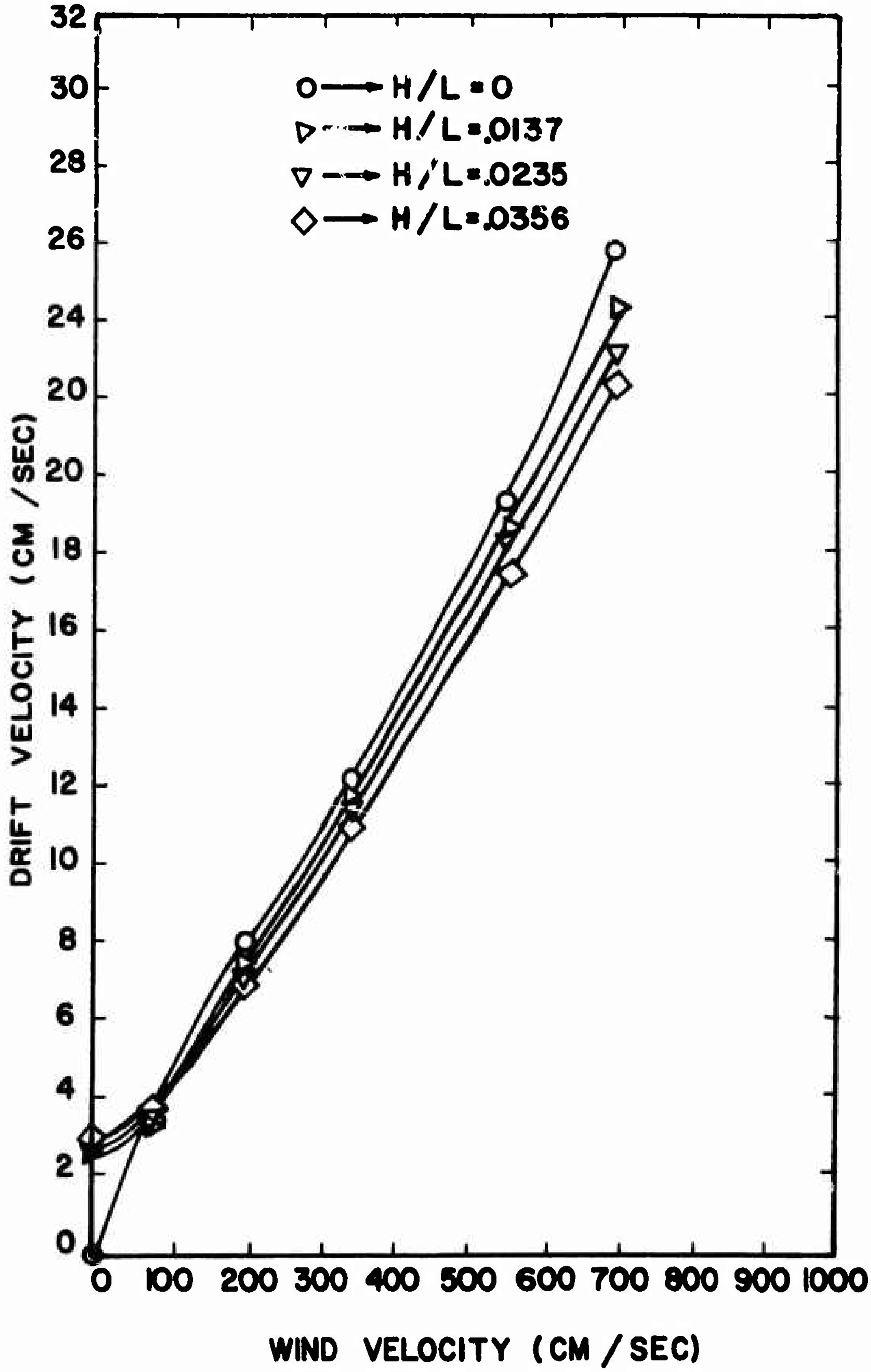

Figure 5. The effect of wave steepness and wind velocity on drift velocity (low to moderate H/L)

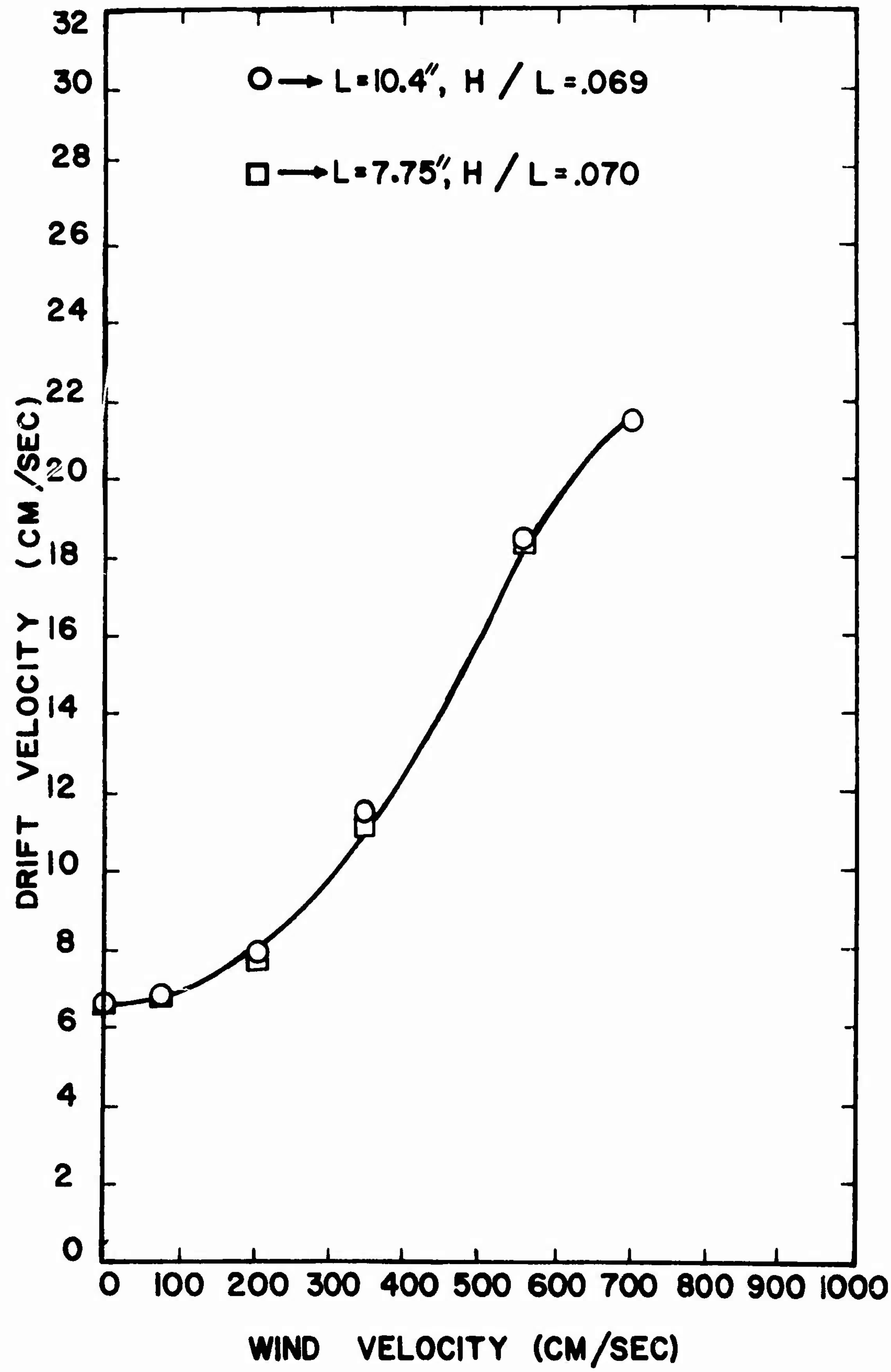

Figure 6. The effect of wave length on drift velocity.

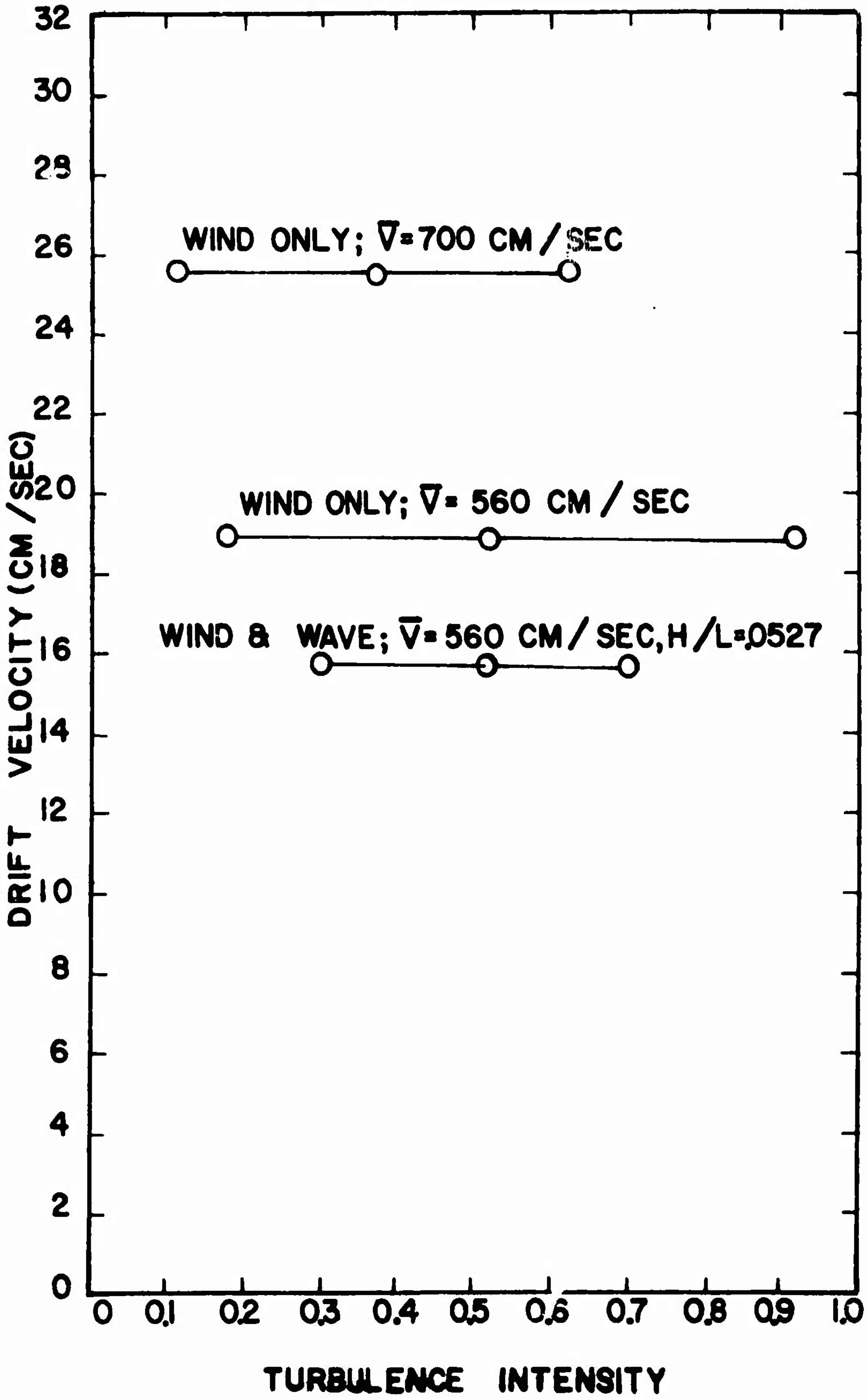

Figure 7. The effect of free stream turbulence on the drift velocity (measurements made 24.13 cm above water surface)

transfer is used to increase the drift velocity or perhaps to cause physical distortion of the wave profiles. Figure 7 indicates that turbulence has little, if any, effect on drift velocity either with smooth water or with wind and waves coupled together. This leads to the conclusion that any increase in momentum transfer to the water, as a result of turbulence, is dissipated by causing a distortion of the wave shape of profile. The turbulence intensity ranged between 0.3 and 0.6 for the data reported in Figure 3. In this case, turbulence intensity is defined as the root mean square value of the velocity fluxuation divided by the average total velocity. Air turbulence field measurements over the ocean have been reported [29, 30] in the range from 0.05 to 0.33; however, these measurements were made at points up to 10 meters above the water surface. In any event, Figure 7 indicates that the question is not important to the determination of the coupled drift velocity caused by wind and waves.

As mentioned above, the drift velocities were measured by using circular plastic floats of suitable diameter to avoid velocity variation caused by wave length. The width of the floats was found to have no effect on the drift velocity caused by waves. A number of tests were also made to determine if the drift characteristics of an oil lens and a plastic float were the same in the presence of both wind and waves. In all tests, the variation in drfit velocity was less than 2% between the oil floats and the plastic floats. This justifies the use of the plastic floats which are desirable because they do not contaminate the water surface.

The wind fetch over the water surface preceding the test section was about 1.5 meters. This distance did not allow the wind to create waves of any magnitude. This insures independent action between the generated wind and the waves.

The results of the experiments to determine the air flow characteristics in the wind tunnel testsection are shown in Figure 8 through 12. Figure 8 shows the vertical velocity profiles at the center of the wind tunnel test section. All velocity profiles are shown to be flat and uniform over the vertical section of the wind tunnel. This effect is similar to conditions on the open ocean. Figure 9 shows the velocity profiles across the width of the wind tunnel at a height of 1.27 centimeters above the water surface. Again, the profiles are flat and uniform over a major portion of the wind tunnel. This insures a uniform air velocity over the float surfaces. Figures 10, 11 and 12 show velocity data at different heights above the water surface. The profiles are skewed at higher velocities near the center of the wind tunnel. This effect was caused by a 90 degree turn of the air flow at the end of the test section. In this series of graphs, the D dimension of the wind tunnel is 45.00 centimeters and the W dimension is 105.00 centimeters.

The tabulated data for this series of experiments is presented in Appendix number 1.

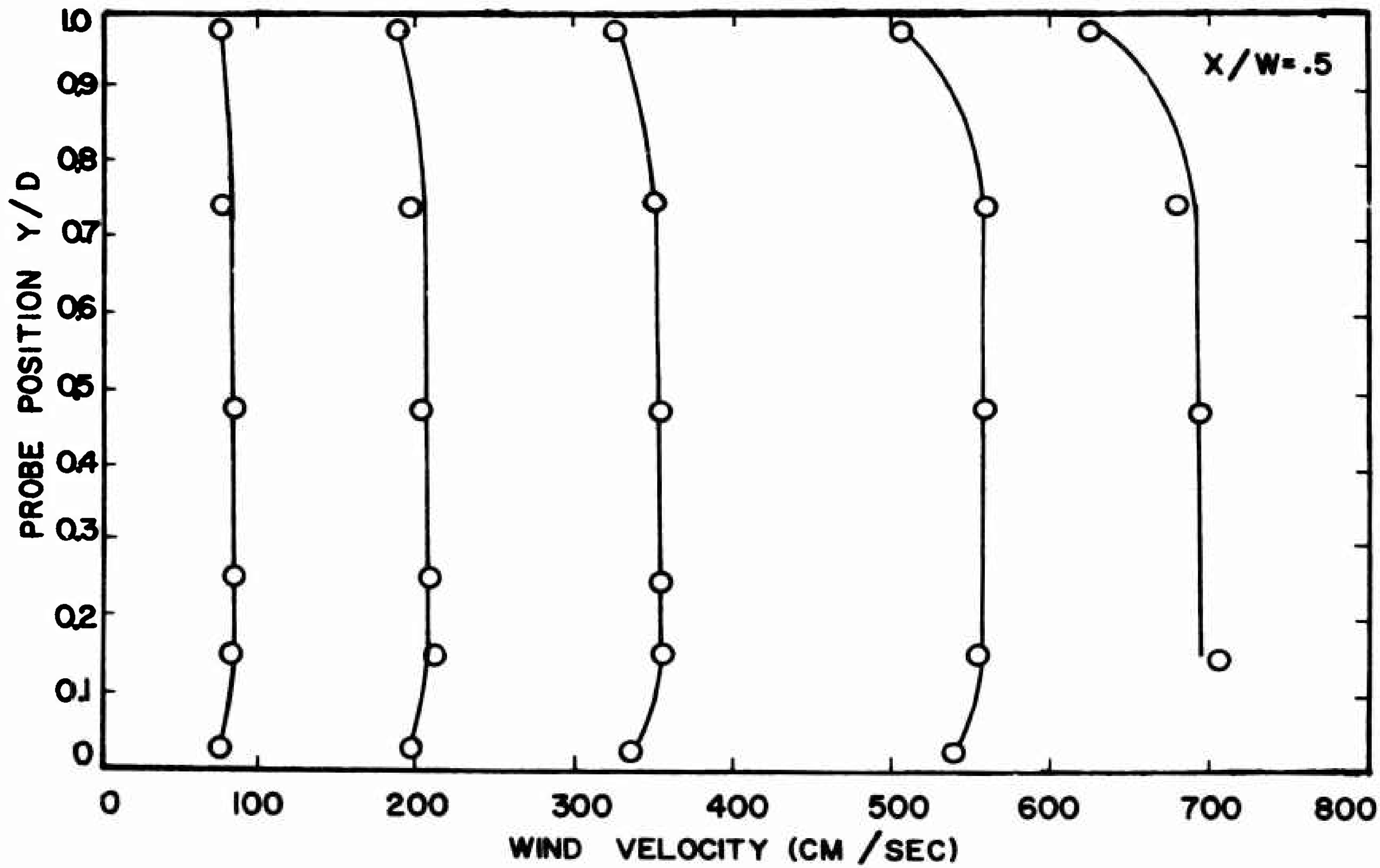

Figure 8. Air velocity profiles between the water surface and the top of the wind tunnel (probe positioned in the center of the tunnel)

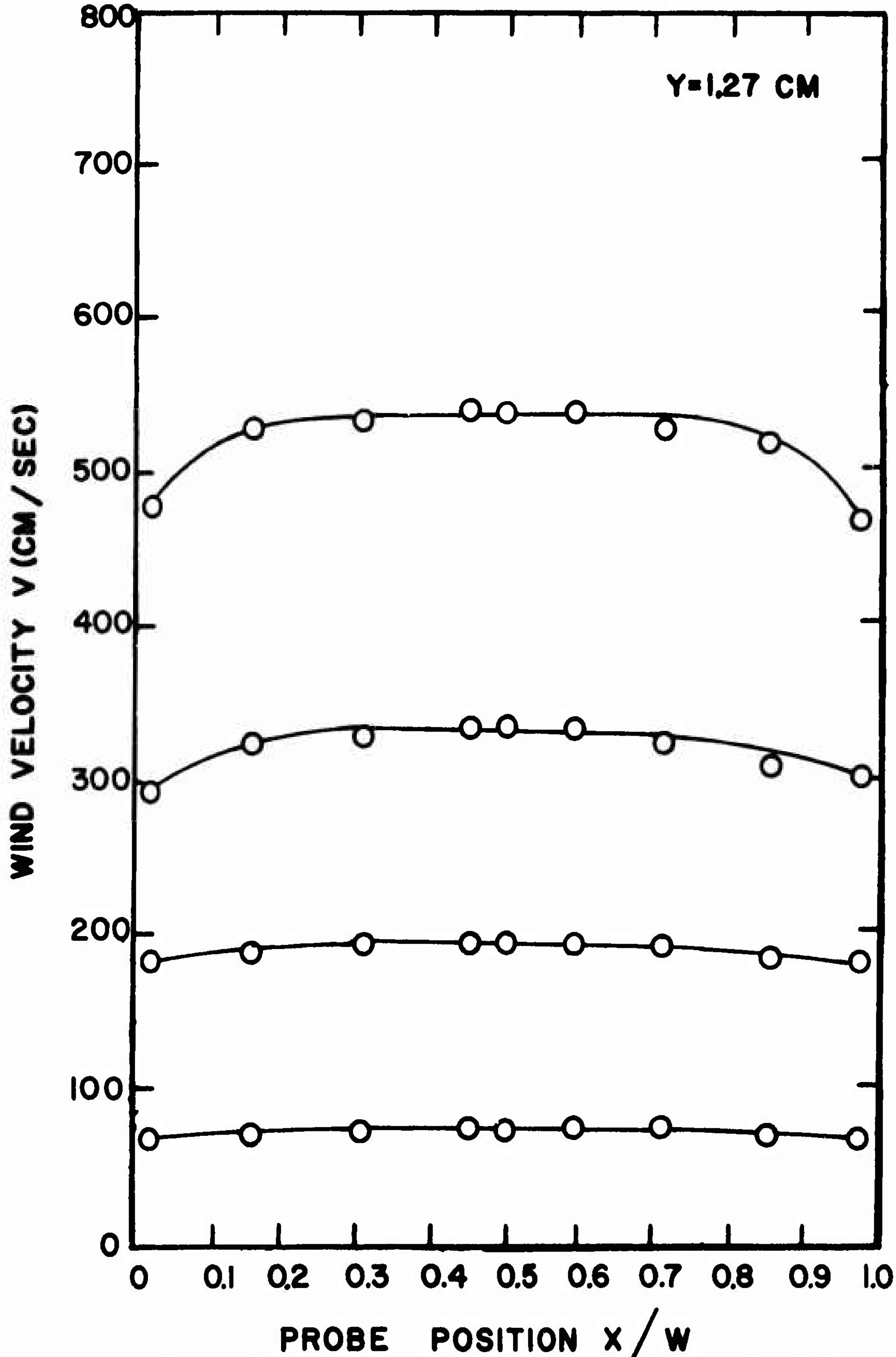

Figure 9. Air velocity profiles across the wind tunnel at 1.27 cm above the water surface.

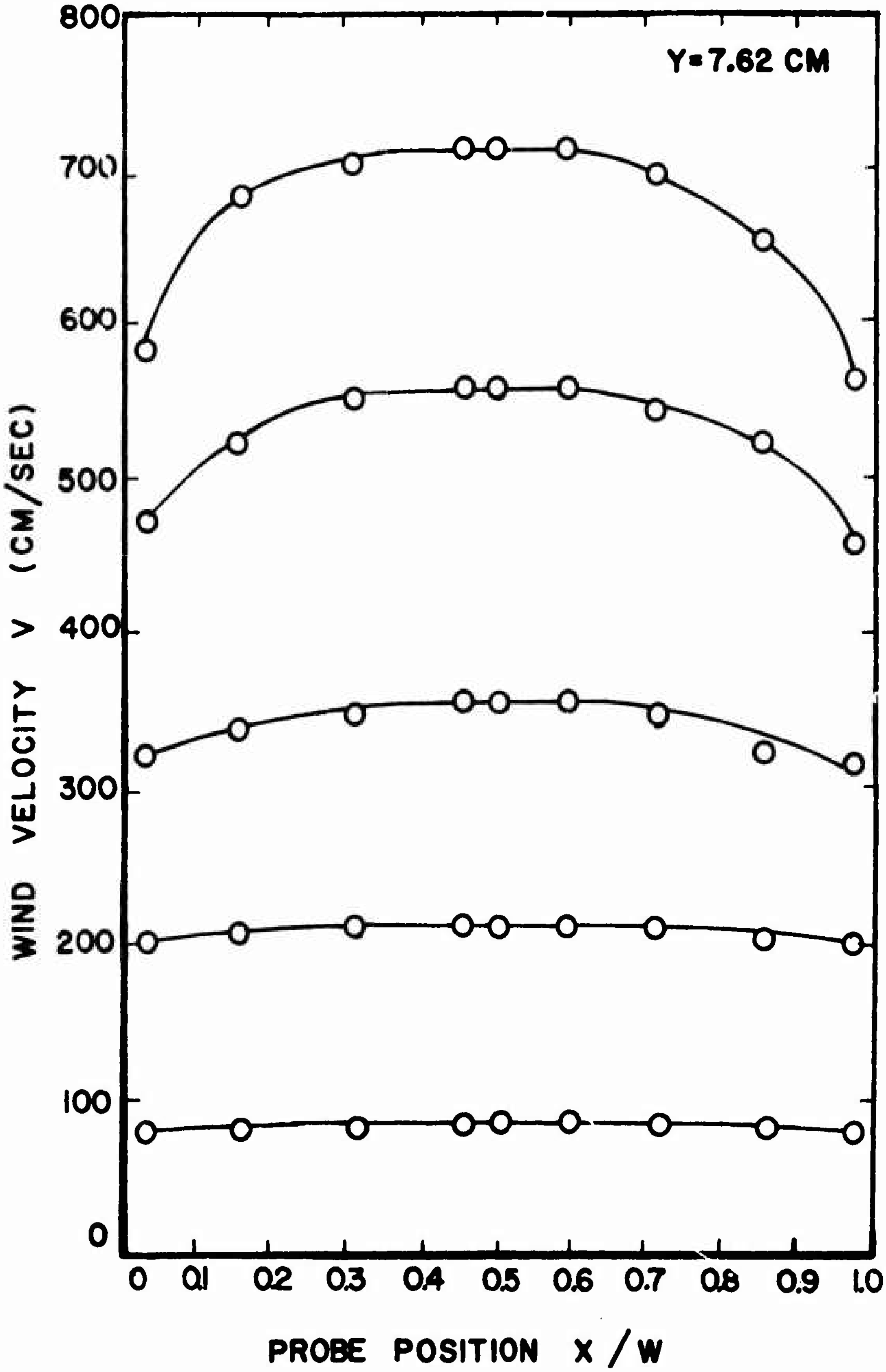

Figure 10. Air velocity profiles across the wind tunnel at 7.62 cm above the water surface.

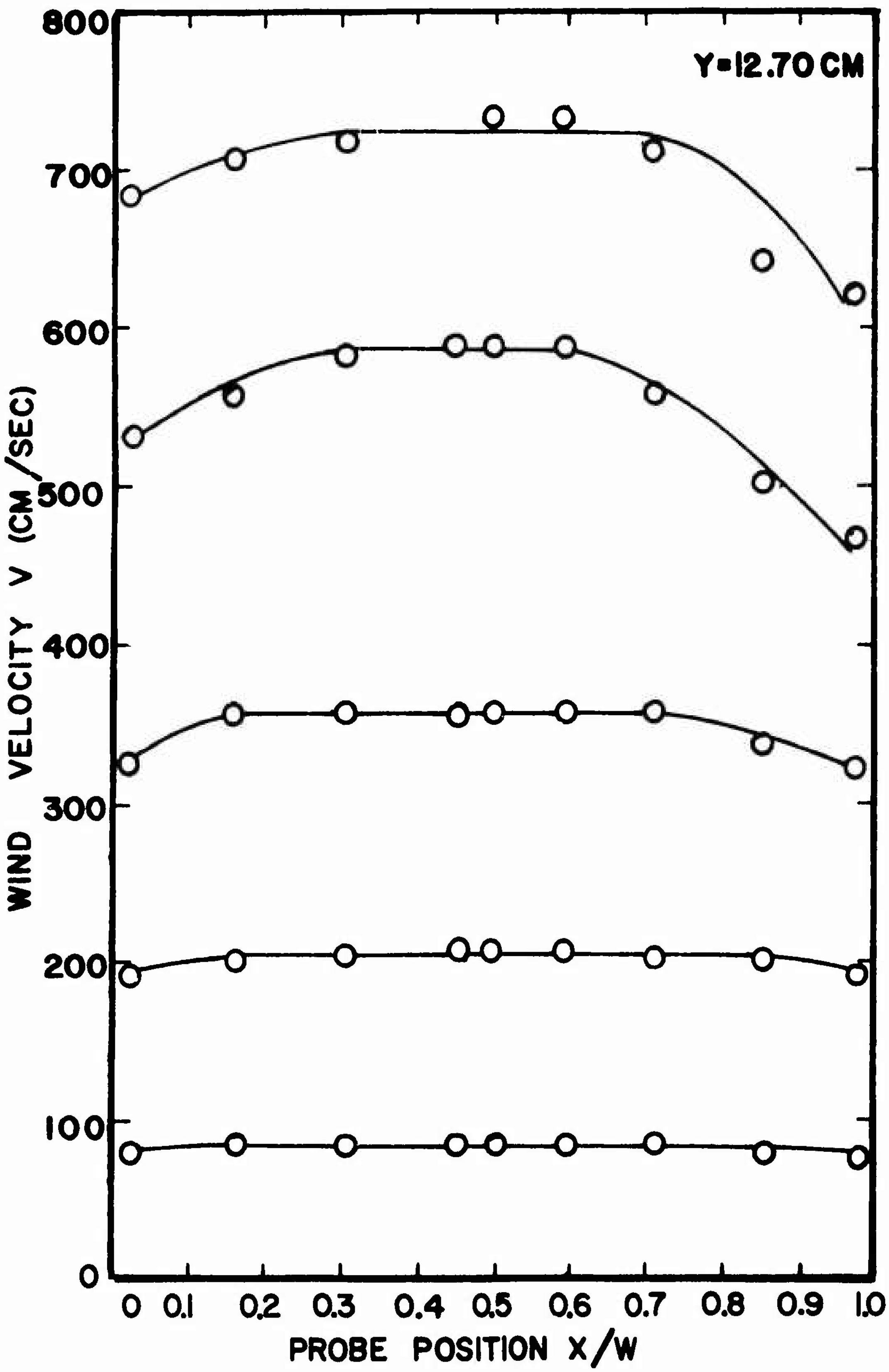

Figure 11. Air velocity profiles across the wind tunnel at 12.70 cm above the water surface.

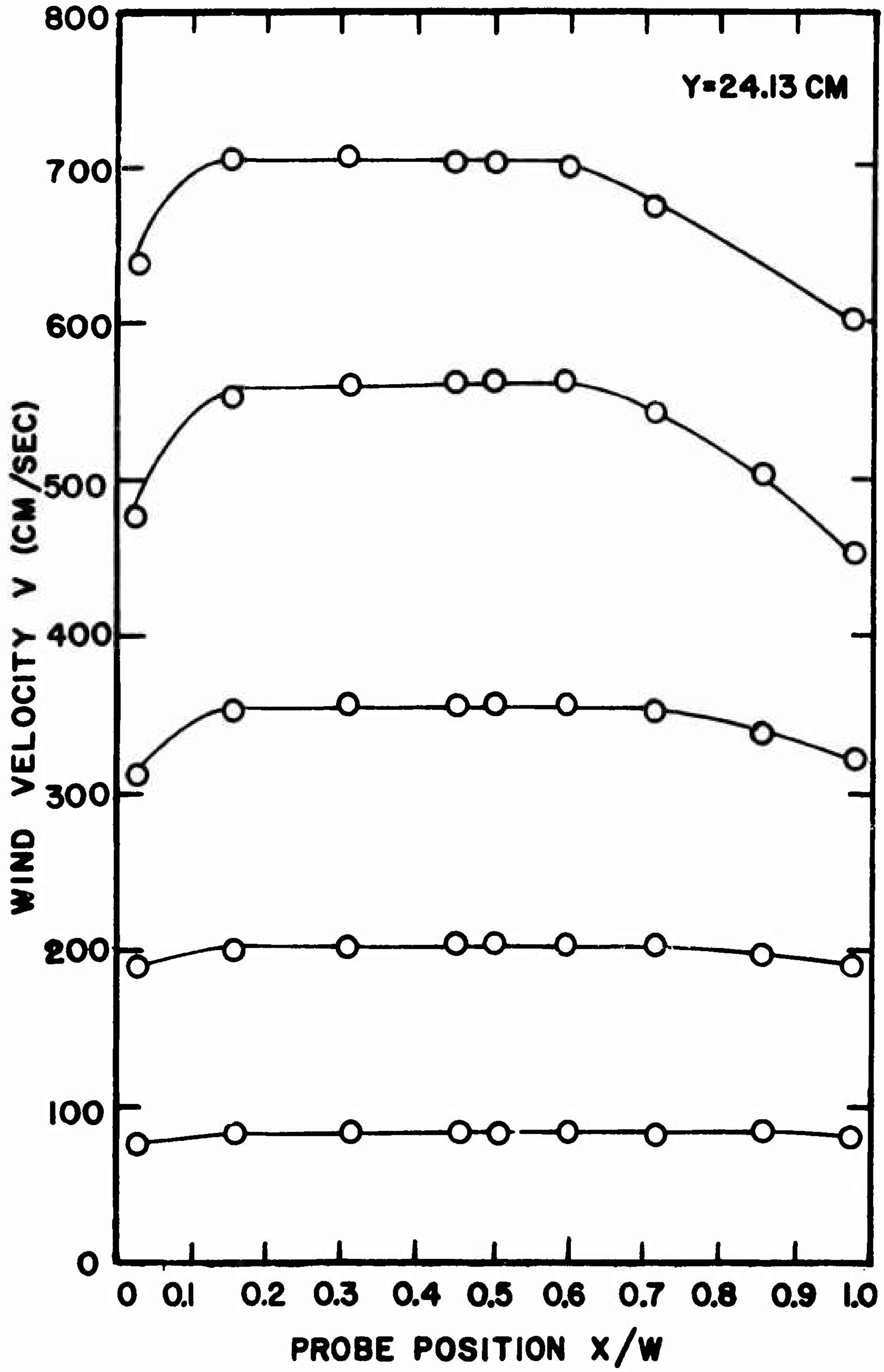

Figure 12. Air velocity profiles across the wind tunnel at 24.13 cm above the water surface.

The Case of Wind and Waves Traveling in the Opposite Direction

The results of the surface drift velocity experiments with the wind and waves traveling in the opposite direction are shown in Figure 13 and Figure 14. Experimental results are presented for free stream wind velocity ($\bar{V}$) from zero to 700 cm/sec; the wave steepness ranged from zero to 0.0705.

It can be seen from Figure 13 that the wind effect is not always the dominant effect. In both Figure 13 and Figure 14 the positive drift is assumed to be in the same direction as the wind. At low wind velocity (below 200 cm/sec) the wave induced drift effect dominates the mechanism. At high wind velocity (above 600 cm/sec) the wind is shown to be the dominant factor to the net coupled drift velocity. In fact, at high wind velocity the waves do not produce any counter drift effect. Figure 13 also shows the conditions at which the wind drift and wave drift effect cancel each other to produce a zero net drift. Figure 14 shows the effect of wave steepness on the net coupled drift caused by opposed wind and waves. Steep waves are shown to have the greatest capacity for opposing the wind drift effect. Again, Figure 14 shows that at a wind speed of 700 cm/sec the waves produced no counter drift effects. The tabulated data for this series of experiments is presented in Appendix number 2.

The Case of Wind and Waves Traveling at Fixed Angles to Each Other

The arrangement of the wind tunnel with respect to the wave tank is shown in Figure 15. Experiments were conducted with the wind tunnel at 90 degrees, 35 degrees, and 10 degrees to the wave channel. Rational results were not obtainable

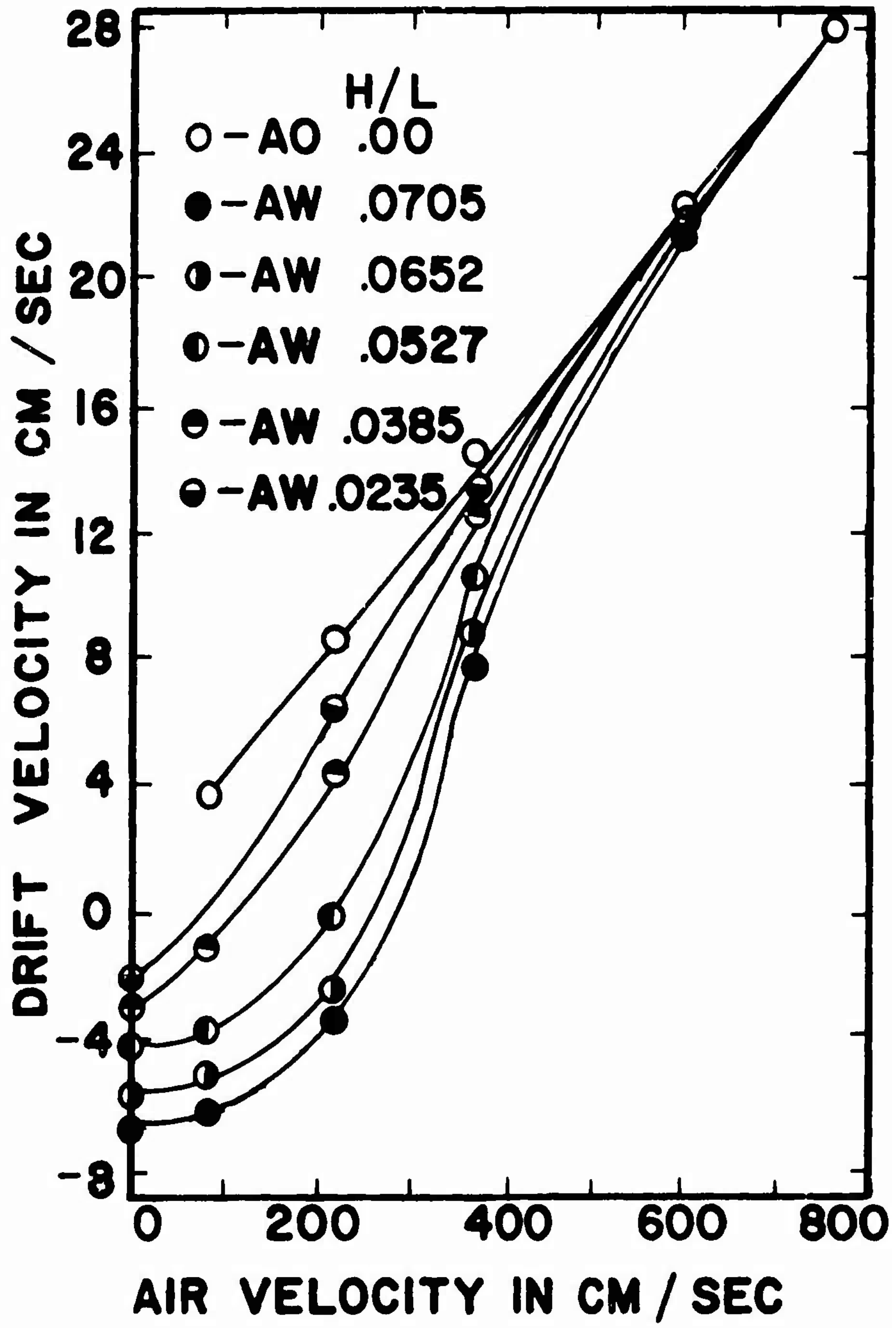

Figure 13 The Effect of Wind Velocity and Waves on the Surface Drift of Oil; Wind and Waves Traveling in Opposite Directions.

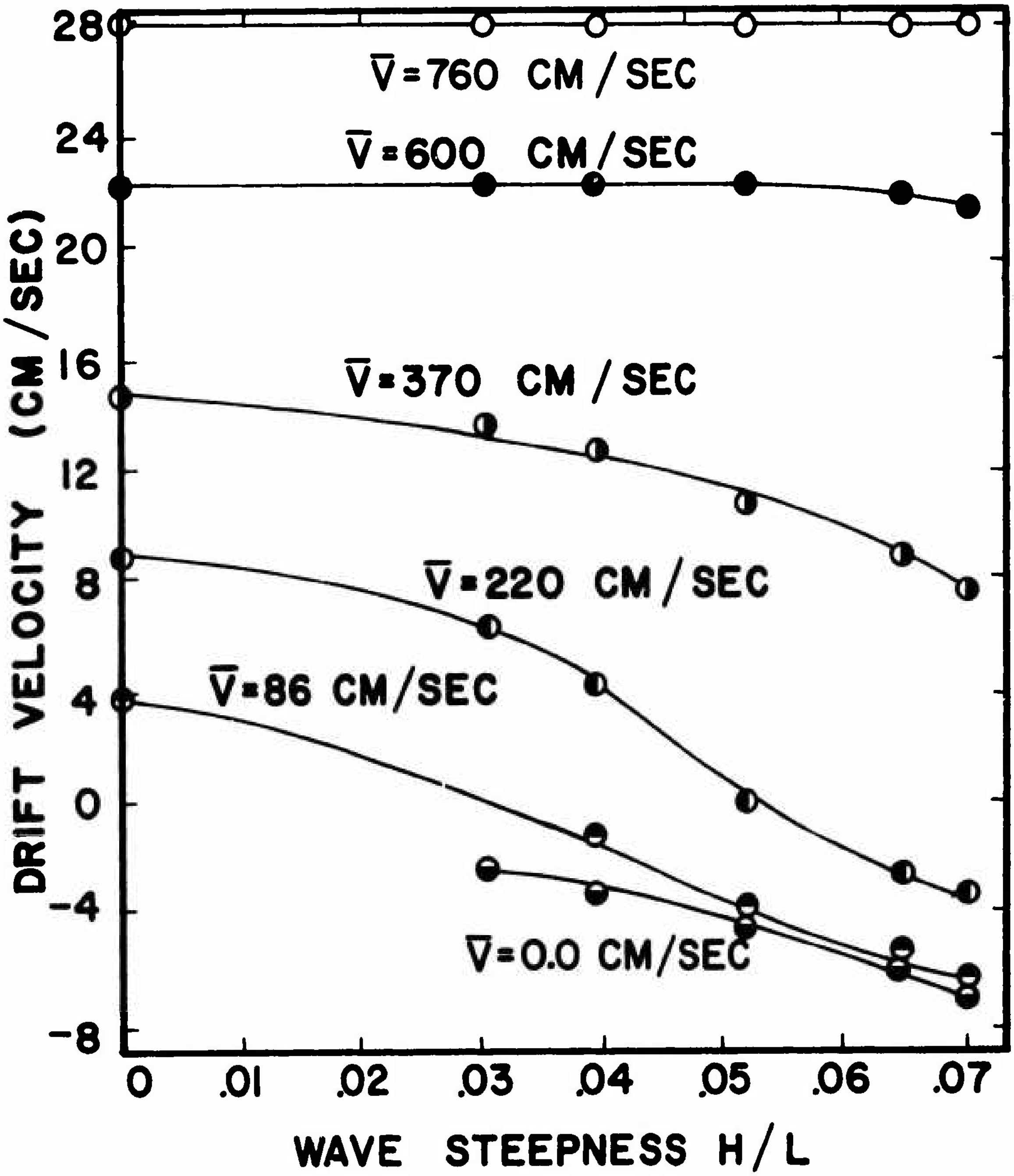

Figure 14 The Effect of Wave Steepness and Wind Velocity on the Surface Drift of Oil; Wind and Waves Traveling in Opposite Directions.

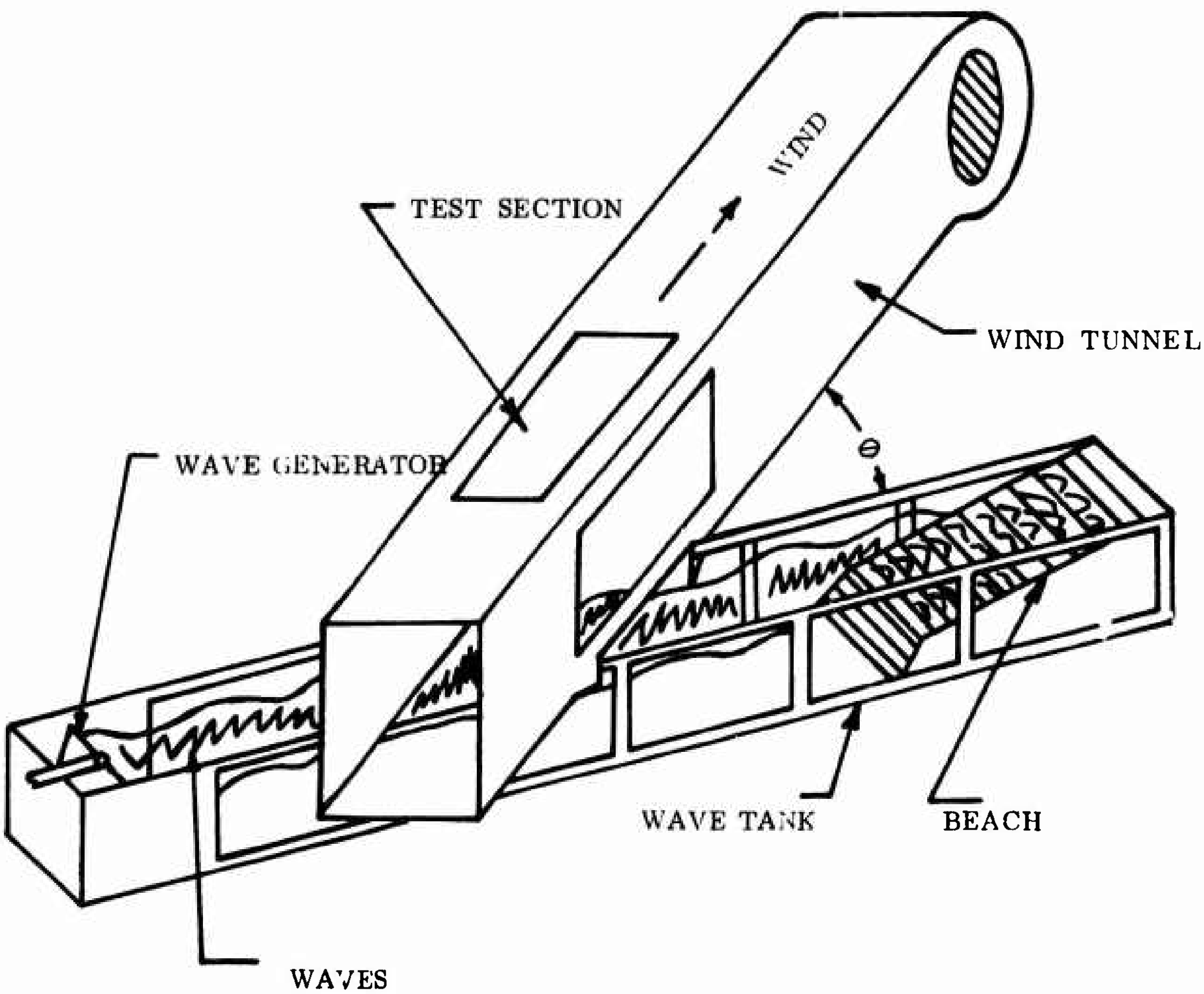

Figure 15. Wind - wave tank (fixed angle experiment)

when the wind tunnel was at 90 and 35 degrees. The reason is twofold; first, the effective entrance length for the airflow was reduced to less than 0.1 meter which was not enough to provide a steady state flow vector over the test section, second, a flow vortex and air velocity decay near the water surface was caused by virtue of the fact that the water level had to be lower than the wind tunnel floor. The tests showed that these effects did not allow a full development of the wind contribution to drift. For example, the drift without waves present was only about 0.1% to 1.0% of the wind velocity compared to the 2.84% to 4.75% range when the wind tunnel was at 0 degree to the wave channel.

The data for the 10 degree case was taken because it represented the largest angle which could be obtained without introducing significantly the problems mentioned above. Figure 16 shows a comparison of the drift velocity for the 10 degree and the 0 degree cases. Figure 16 shows that within experimental accuracy the drift veloc ty vector for the 10 degree data was identical in magnitude and direction to the drift vector for the 0 degree case (wind and waves in the same direction). This indicates that no unexpected phenomena takes place when the angle between the wind and waves is increased from zero to 10 degrees. Figure 17 shows that this range of angles accounts for about 40 percent of the frequency of occurrence for open ocean wind-wave conditions. This rather high frequency factor makes the above conclusion quite important.

Figure 17 presents data from field observations about the frequency of occurrence of various angles between the wind vector and the wave vector. This

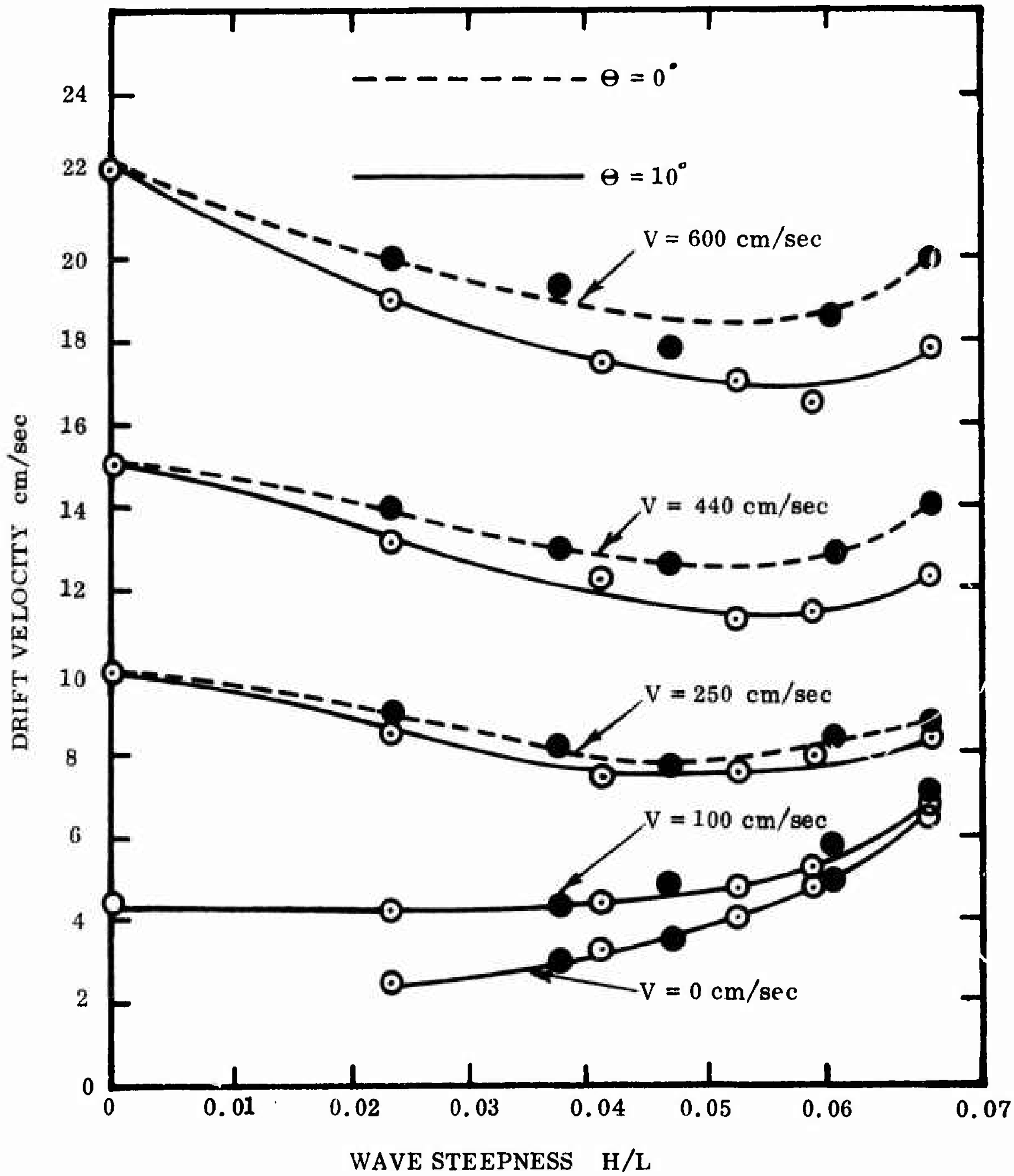

Figure 16. Effect of angle alignment between the wind and waves

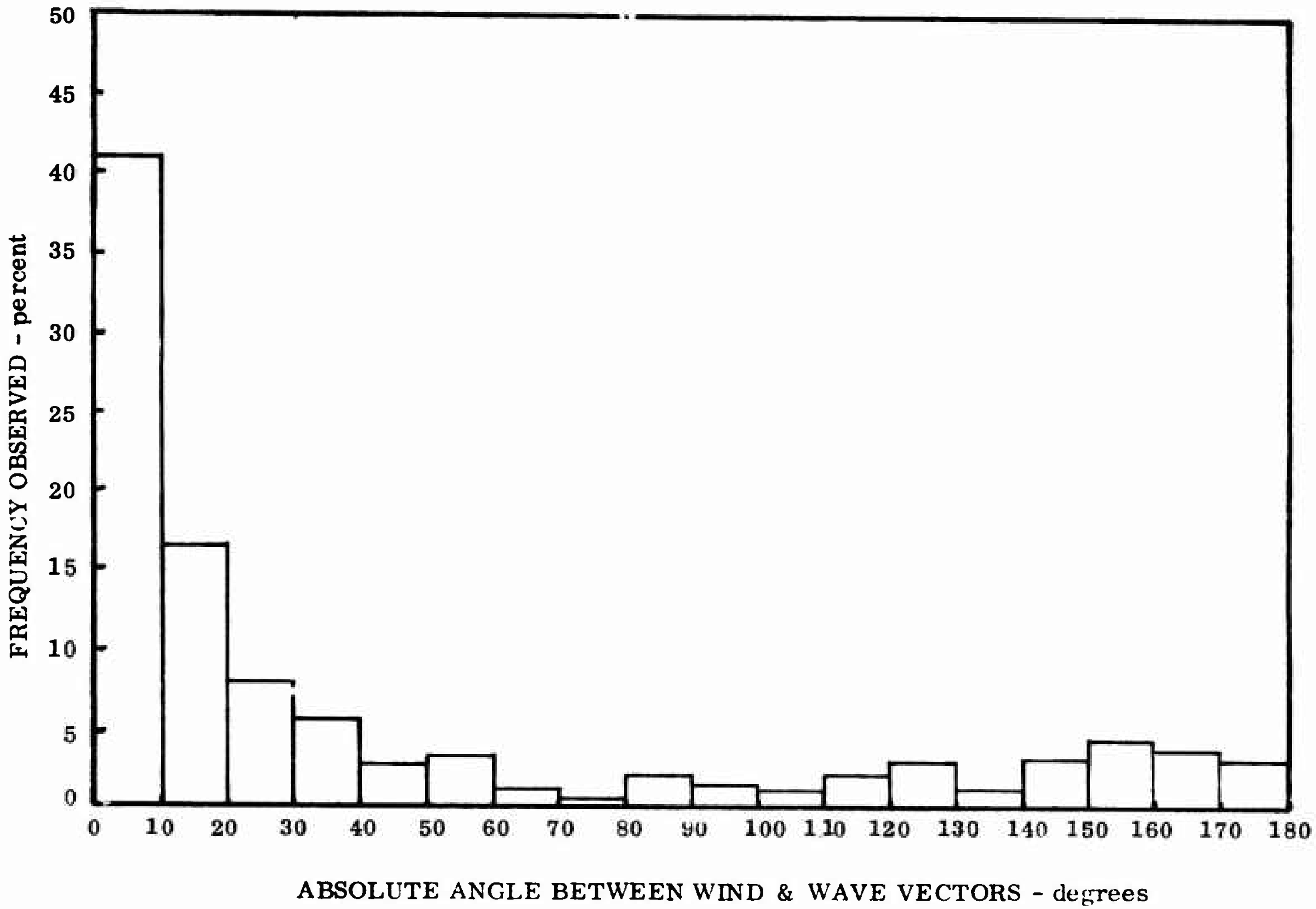

Figure 17. Wind-wave alignment angle frequency

data was taken from U. S. Coast Guard Oceanographic reports no. 25 through 40, and as such represents a wide variety of ocean locations and a time period ranging from 1967 to 1971. Figure 17 indicates that research priorities should be placed on the 0 degree wind-wave interaction case since in the field the 0 to 20 degree condition occurs about two thirds of the time.

SUMMARY AND CONCLUSIONS

The experiments present positive evidence that the wind induced and wave induced drift mechanisms interact in a complicated way. It is clear that the wave drift and the wind drift are not additive over all regimes of wind speed. At low wind speeds the wave drift provides an augmentation to the wind drift. However, at higher wind speeds the waves cause a net decrease in the coupled drift velocity. In fact, the wave induced diminishment increases as the wind speed increases. The exact role which turbulence plays is not totally clear. This investigation indicates that the turbulence intensity has no affect on surface drift. However, the surface drift diminishment when waves are coupled with wind is surely due to turbulent phenomena. In light of the experimental evidence in this study, it appears that the surface shear stress fluctuates over the surface of a water wave. This complicated fluctuation is due to the fluid motion characteristics which are a natural part of water waves and may result in part from the separated turbulent air flow in the wave trough. Any future attempt to generate a mathematical model should include the effect of finite float size where the shear stress causing movement is integrated over its surface.

Waves traveling in the opposite direction to the wind can have a very large effect on the drift velocity, especially at low wind speeds. It is important to note however that this situation occurs less than three percent of the time. The wind-wave vectors are from 160 to 180 degrees apart less than 10 percent of the time. At high wind speeds, opposed waves have little if any effect on the drift speed.

The effect of wind and waves which travel at fixed angles to each other is small and the occurrence is infrequent. It is thus concluded that this effect can be neglected in a drift simulation without introducing serious error.

The case where wind and waves travel in the same direction occurs most frequently and the effect of waves on drift velocity is significant. It is thus recommended that the coupled parallel and codirectional effects of wind and waves be included in a drift simulation. Failure to include this effect could lead to serious predictive errors in the path of an oil spill.

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APPENDIX NUMBER ONE - WIND AND WAVES UNIDIRECTIONAL

DATA SHEET NOMENCLATURES

WO - Wave only

AO - Air only

WA - Wave plus Air

H - Wave Height in Centimeters

L - Wave Length in Centimeters

T_W - Water Temperature in degrees Fahrenheit

T_A - Air Temperature in degrees Fahrenheit

P_B - Barometric Pressure

V_B - D. C. Voltmeter reading at Bridge output in Volts

V_T - R. M. S. Voltmeter reading at Bridge output in Volts

$\bar{V}$ - Freestream wind velocity in cm/sec

T_t - Trial Drift Time in Seconds

$\ddot{T}$ - Average Drift Time in Seconds

V_d - Average drift velocity of surface float in cm/sec

I_t - Intensity of Turbulence

RAW EXPERIMENTAL DATA

Float size - 38.1 centimeters

Float material - flexible plastic

Length of the test section - 1.20 meters

Run No.		1	2	3	4	5	6
H		1.85	--	1.85	--	1.85	--
L		26.40	--	26.40	--	26.40	--
H/L		0.0695	--	0.0695	--	0.0695	--
T_W		68	68	68	68	68	68
T_A		72	72	72	72	72	72
V_B		--	6.52	6.52	7.02	7.02	7.35
V_T		--	0.21	0.21	0.40	0.40	0.48
$\bar{V}$		--	80.00	80.00	205.00	205.00	350.00
Mechanism		WO	AO	WA	AO	WA	AO
	1	18.00	33.00	17.00	14.20	14.80	10.00
	2	17.50	32.00	17.20	15.00	15.00	9.00
T_t	3	18.00	31.80	16.85	14.80	15.10	9.50
	4	17.80	32.00	18.00	14.60	14.50	9.50
	5	18.00	31.90	18.00	14.00	14.90	9.40
$\bar{T}$		17.86	32.14	17.40	14.50	14.80	9.60
V_d		6.55	3.65	6.74	8.101	7.94	12.28
I_t		--	0.446	0.446	0.607	0.607	0.617

Run No.		7	8	9	10	11	12
H		1.85	--	1.85	--	1.85	1.625
L		26.40	--	26.40	--	26.40	26.40
H/L		0.0695	--	0.0695	--	0.0695	0.061
T_W		68	68	68	68	68	67.5
T_A		72	72	72	72	72	69
V_B		7.35	7.72	7.72	7.93	7.93	--
V_T		0.48	0.48	0.48	0.57	0.57	--
$\bar{V}$		350.00	560.00	560.00	700.00	700.00	--
Mechanism		WA	AO	WA	AO	WA	WO
	1	10.00	5.80	6.15	4.50	5.20	27.50
	2	10.00	6.00	6.55	4.40	5.50	24.00
T_t	3	10.10	6.00	6.00	4.60	5.50	24.00
	4	10.20	6.00	6.10	4.50	5.50	23.60
	5	10.00	5.80	6.10	4.40	5.50	24.20
$\bar{T}$		10.06	6.00	6.20	4.50	5.50	23.96
V_d		11.60	19.55	18.50	26.10	21.35	4.90
I_t		0.617	0.53	0.53	0.58	0.58	--

Run No.		13	14	15	16	17	18
H		1.625	1.625	1.625	1.625	1.625	1.25
L		26.40	26.40	26.40	26.40	26.40	26.40
H/L		0.061	0.061	0.061	0.061	0.061	0.0471
T_W		67.5	67.5	67.5	67.5	67.5	71.5
T_A		69	69	69	69	69	76
V_B		6.52	7.02	7.35	7.72	7.93	--
V_T		0.21	0.40	0.48	0.56	0.40	--
$\bar{V}$		80.00	205.00	350.00	560.00	700.00	--
Mechanism		AW	AW	AW	AW	AW	WO
	1	23.50	15.00	10.75	6.70	6.00	34.00
	2	22.00	15.00	10.50	6.80	6.00	33.00
T_t	3	19.50	15.00	11.00	6.60	5.90	32.00
	4	22.00	18.00	10.50	6.65	6.10	32.50
	5	21.00	15.20	10.50	6.70	6.00	32.00
$\bar{T}$		21.70	15.00	10.65	6.70	6.00	32.40
V_d		5.43	7.825	11.05	17.50	19.58	3.63
I_t		0.446	0.607	0.617	0.617	0.41	--

Run No.		19	20	21	22	23	24
H		1.25	1.25	1.25	1.25	1.25	0.94
L		26.40	26.40	26.40	26.40	26.40	26.40
H/L		0.0471	0.0471	0.0471	0.0471	0.0471	0.0356
T_W		71.5	71.5	71.5	71.5	71.5	71
T_A		76	76	76	76	76	75
V_B		6.52	7.02	7.35	7.72	7.93	--
V_T		0.21	0.40	0.48	0.56	0.40	--
$\bar{V}$		80.00	205.00	350.00	560.00	700.00	--
Mechanism		WA	WA	WA	WA	WA	WO
	1	32.00	16.00	11.35	7.30	5.60	40.00
	2	25.20	16.30	11.50	7.10	5.60	41.00
T_t	3	26.50	15.85	11.10	7.50	5.40	41.10
	4	26.70	15.50	11.60	7.30	5.70	40.50
	5	26.30	16.50	11.50	7.25	5.60	39.80
$\bar{T}$		26.20	16.30	11.40	7.30	5.60	40.30
V_d		4.48	7.20	10.30	16.10	20.95	2.91
I_t		0.446	0.607	0.617	0.617	0.41	--

Run No.		25	26	27	28	29	30
H		0.94	0.94	0.94	0.94	0.94	0.62
L		26.40	26.40	26.40	26.40	26.40	26.40
H/L		0.0356	0.0356	0.0356	0.0356	0.0356	0.0235
T_W		71	71	71	71	71	73
T_A		75	75	75	75	75	77
V_B		6.52	7.02	7.35	7.72	7.93	--
V_T		0.21	0.40	0.48	0.48	0.57	--
$\bar{V}$		80.00	205.00	350.00	560.00	700.00	--
Mechanism		AW	AW	AW	AW	AW	WO
	1	31.50	16.80	10.80	6.85	5.25	53.00
	2	32.00	16.50	10.60	6.65	5.30	48.00
T_t	3	31.50	16.80	10.50	6.70	5.25	48.50
	4	32.20	17.00	10.90	6.60	5.30	49.00
	5	32.50	16.50	10.00	6.65	5.35	50.00
$\bar{T}$		31.95	16.70	10.70	6.70	5.30	48.50
V_d		3.68	7.05	11.00	17.50	22.35	2.41
I_t		0.446	0.607	0.617	0.53	0.58	--

Run No.		31	32	33	34	35	36
H		0.62	0.62	0.62	0.62	0.62	0.705
L		26.40	26.40	26.40	26.40	26.40	52.80
H/L		0.0235	0.0235	0.0235	0.0235	0.0235	0.0137
T_W		73	73	73	73	73	69
T_A		77	77	77	77	77	74
V_B		6.52	7.02	7.35	7.72	7.93	--
V_T		0.21	0.40	0.48	0.56	0.57	--
$\bar{V}$		80.00	205.00	350.00	560.00	700.00	--
Mechanism		WA	WA	WA	WA	WA	WO
	1	40.00	16.80	10.50	6.20	4.80	75.50
	2	34.00	16.50	10.30	6.20	5.00	63.00
T_t	3	33.00	16.40	10.30	6.50	5.20	61.00
	4	34.50	16.50	10.30	6.40	5.00	64.00
	5	34.00	16.40	10.40	6.30	5.20	62.00
$\bar{T}$		34.20	16.50	10.30	6.35	5.05	62.50
V_d		3.44	7.13	11.42	18.55	23.25	1.885
I_t		0.446	0.607	0.617	0.617	0.58	--

Run No.		37	38	39	40	41	42
H		0.705	0.705	0.705	0.705	0.705	1.39
L		52.80	52.80	52.80	52.80	52.80	19.70
H/L		0.0137	0.0137	0.0137	0.0137	0.0137	0.0705
T_W		69	69	69	69	69	68
T_A		74	74	74	74	74	72
V_B		6.52	7.02	7.35	7.72	7.93	--
V_T		0.21	0.40	0.48	0.48	0.57	--
$\bar{V}$		80.00	205.00	350.00	560.00	700.00	--
Mechanism		WA	WA	WA	WA	WA	WO
	1	37.80	16.40	10.00	6.20	4.75	18.50
	2	36.50	16.50	9.90	6.35	4.80	18.30
T_t	3	37.00	16.00	10.10	6.25	4.80	18.00
	4	36.40	16.00	9.85	6.10	4.80	18.40
	5	37.00	15.80	10.10	6.20	4.85	17.50
$\bar{T}$		36.70	16.15	10.00	6.25	4.80	18.10
V_d		3.21	7.28	11.75	18.85	24.45	6.50
I_t		0.446	0.607	0.617	0.53	0.58	--

Run No.		43	44	45	46	47	48
H		1.39	1.39	1.39	1.39	--	--
L		19.70	19.70	19.70	19.70	--	--
H/L		0.0705	0.0705	0.0705	0.0705	--	--
T_W		68	68	68	68	68	68
T_A		72	72	72	72	72	72
V_B		6.52	7.02	7.35	7.72	7.93	7.93
V_T		0.21	0.40	0.48	0.48	0.62	0.38
$\bar{V}$		80.00	205.00	350.00	560.00	700.00	700.00
Mechanism		WA	WA	WA	WA	AO	AO
	1	16.50	15.50	10.90	6.30	4.60	4.60
	2	17.50	15.00	11.00	6.40	4.60	4.60
T_t	3	18.00	15.40	10.50	6.50	4.60	4.60
	4	18.00	14.80	10.20	6.30	--	--
	5	17.90	15.50	11.50	6.40	--	--
$\bar{T}$		17.85	15.25	10.65	6.40	4.60	4.60
V_d		6.58	7.70	11.05	18.40	25.50	25.50
I_t		0.446	0.607	0.617	0.53	0.625	0.387

Run No.		49	50	51	52	53	54
H		--	--	--	--	1.39	1.34
L		--	--	--	--	26.40	26.40
H/L		--	--	--	--	0.0527	0.0527
T_W		68	68	68	68	69	69
T_A		72	72	72	72	73	73
V_B		7.93	7.72	7.72	7.72	7.72	7.72
V_T		0.12	0.85	0.48	0.165	0.27	0.47
$\bar{V}$		700.00	560.00	560.00	560.00	560.00	560.00
Mechanism		AO	AO	AO	AO	WA	WA
	1	4.60	6.15	6.20	6.20	7.45	7.50
	2	4.50	6.20	6.20	6.25	7.45	7.55
T_t	3	4.60	6.25	6.25	6.15	7.50	7.40
	4	--	--	--	--	7.55	7.50
	5	--	--	--	--	--	7.60
$\bar{T}$		4.60	6.20	6.20	6.20	7.49	7.51
V_d		25.50	18.95	18.95	18.95	15.70	15.62
I_t		0.122	0.923	0.525	0.182	0.299	0.52

Run No.		55
H		1.39
L		26.40
H/L		0.0527
T_W		69
T_A		73
V_B		7.72
V_T		0.64
$\bar{V}$		560.00
Mechanism		WA
	1	7.60
	2	7.50
T_t	3	7.40
	4	7.50
	5	--
$\bar{T}$		7.50
V_d		15.65
I_t		0.703

APPENDIX NUMBER TWO

WIND AND WAVES IN OPPOSITE DIRECTIONS

DATA SHEET NOMENCLATURES

WO - Wave only

AO - Air only

WA - Wave plus Air

H - Wave Height in Centimeters

L - Wave Length in Centimeters

T_W - Water Temperature in degrees Fahrenheit

T_A - Air Temperature in degrees Fahrenheit

P_B - Barometric Pressure

V_B - D. C. Voltmeter reading at Bridge output in Volts

dV_B - Fluctuation of D. C. Voltmeter reading at Bridge output in Volts

V_T - R. M. S. Voltmeter reading at Bridge output in Volts

$\bar{V}$ - Freestream wind velocity in cm/sec

T_t - Trial Drift Time in Seconds

$\bar{T}$ - Average Drift Time in Seconds

V_d - Average drift velocity of surface float in cm/sec

I_t - Intensity of Turbulence

-Ve - Sign of Average drift velocity (V_d) indicates float travels in the direction of waves

RAW EXPERIMENTAL DATA

Float size - 38.1 centimeters
Float material - flexible plastic
Length of the test section - 1.20 meters

Run No.		1	2	3	4	5	6
H		1.862	--	1.862	--	1.862	--
L		26.40	--	26.40	--	26.40	--
H/L		0.0705	--	0.0705	--	0.0705	--
T_W		63	63	63	63	63	63
T_A		74	74	74	74	74	74
V_B		--	3.88	3.88	3.74	3.74	3.53
dV_B		--	0.20	0.20	0.28	0.18	0.11
V_T		--	0.27	0.27	0.26	0.26	0.29
$\bar{V}$		--	760	760	600	600	370
Mechanism		WO	AO	AW	AO	AW	AO
	1	17.00	4.40	4.50	5.30	5.50	8.10
	2	16.80	4.00	4.10	5.20	5.50	8.20
T_t	3	17.20	4.20	4.00	5.40	5.60	8.10
	4	17.00	4.30	4.20	5.30	5.40	7.90
	5	18.00	4.20	4.20	5.40	5.50	8.00
$\bar{T}$		17.00	4.20	4.20	5.30	5.50	8.10
V_d		-6.90	27.95	27.95	22.20	21.38	14.48
I_t		--	0.405	0.405	0.402	0.402	0.294

Run No.		7	8	9	10	11	12
H		1.862	--	1.862	--	1.862	1.728
L		26.40	--	26.40	--	26.40	26.40
H L		0.0705	--	0.0705	--	0.0705	0.0652
T_W		63	63	63	63	63	63
T_A		74	74	74	74	74	74
V_B		3.53	3.33	3.33	3.07	3.07	--
dV_B		0.11	0.09	0.09	0.11	0.11	--
V_T		0.29	0.26	0.26	0.24	0.29	--
$\bar{V}$		370	220	220	86	86	--
Mechanism		AW	AO	AW	AO	AW	WO
	1	15.00	13.50	32.00	32.00	18.00	21.00
	2	14.50	14.00	35.00	31.50	19.00	19.00
T_t	3	15.40	13.00	34.50	32.40	18.40	20.00
	4	14.00	13.80	35.00	31.80	18.50	18.00
	5	16.00	13.20	34.00	32.10	18.60	20.00
$\bar{T}$		15.00	13.50	34.10	32.00	18.50	20.00
V_d		7.825	8.70	-3.44	3.67	-6.35	-5.875
I_t		0.294	0.297	0.297	0.49	0.49	--

Run No.		13	14	15	16	17	18
H		1.728	1.728	1.728	1.728	1.728	1.39
L		26.40	26.40	26.40	26.40	26.40	26.40
H/L		0.0652	0.0652	0.0652	0.0652	0.0652	0.0527
T_W		63	63	63	63	63	60
T_A		74	74	74	74	74	73
V_B		3.88	3.74	3.53	3.33	3.07	--
dV_B		0.20	0.18	0.10	0.09	0.11	--
V_T		0.27	0.29	0.26	0.26	0.29	--
$\bar{V}$		760	600	370	220	86	--
Mechanism		AW	AW	AW	AW	AW	WO
	1	4.10	5.40	14.00	46.00	22.00	27.00
	2	4.30	5.30	14.00	44.00	21.00	26.50
T_t	3	4.20	5.50	13.50	44.00	23.00	28.00
	4	4.00	5.00	13.50	44.50	22.00	29.00
	5	4.20	5.40	12.00	44.00	22.00	28.00
$\bar{T}$		4.20	5.40	13.50	44.00	22.00	28.00
V_d		27.95	21.80	8.70	-2.67	-5.34	-[illegible].19
I_t		0.405	0.425	0.268	0.297	0.49	--

Run No.		19	20	21	22	23	24
H		1.39	1.39	1.39	1.39	1.39	1.015
L		26.40	26.40	26.40	26.40	26.40	26.40
H/L		0.0257	0.0257	0.0257	0.0257	0.0257	0.0385
T_W		60	60	60	60	60	60
T_A		73	73	73	73	73	73
V_B		3.88	3.74	3.53	3.33	3.07	--
dV_B		0.20	0.18	0.11	0.09	0.11	--
V_T		0.27	0.26	0.24	0.26	0.29	--
$\bar{V}$		760	600	370	220	86	--
Mechanism		AW	AW	AW	AW	AW	WO
	1	4.00	5.30	10.50	0.00	29.00	39.00
	2	4.20	5.40	11.50	0.00	31.00	35.00
T_t	3	4.20	5.20	10.80	0.00	32.00	39.00
	4	4.30	5.30	11.00	0.00	31.00	39.00
	5	4.25	5.50	11.20	0.00	31.00	40.00
$\bar{T}$		4.20	5.30	11.00	0.00	31.00	39.00
V_d		27.95	22.20	10.65	0.00	-3.78	-3.01
I_t		0.405	0.402	0.294	0.297	0.49	--

Run No.	25	26	27	28	29	30
H	1.015	1.015	1.015	1.015	1.015	0.62
L	26.40	26.40	26.40	26.40	26.40	26.40
H/L	0.0385	0.0385	0.0385	0.0385	0.0385	0.0235
T_W	60	60	60	60	60	61
T_A	73	73	73	73	73	72
V_B	3.88	3.74	3.53	3.33	3.07	--
dV_B	0.20	0.19	0.10	0.09	0.11	--
V_T	0.27	0.29	0.26	0.26	0.29	--
$\bar{V}$	760	600	370	220	86	--
Mechanism	AW	AW	AW	AW	AW	WO
1	4.10	5.20	9.50	26.00	98.00	49.00
2	4.20	5.40	9.20	31.00	85.00	50.00
T_t 3	4.30	5.30	9.50	27.00	89.50	48.00
4	4.20	5.50	9.20	25.00	96.00	49.00
5	4.20	5.20	9.30	27.50	94.00	49.50
$\bar{T}$	4.20	5.30	9.35	27.00	93.00	49.00
V_d	27.95	22.20	12.55	4.35	-1.262	-2.40
I_t	0.405	0.425	0.268	0.297	0.49	--

Run No.		31	32	33	34
H		0.62	0.62	0.62	0.62
L		26.40	26.40	26.40	26.40
H/L		0.0235	0.0235	0.0235	0.0235
T_W		61	61	61	61
T_A		72	72	72	72
V_B		3.88	3.74	3.53	3.33
dV_B		0.20	0.18	0.10	0.11
V_T		0.27	0.26	0.26	0.29
$\bar{V}$		760	600	370	220
Mechanism		AW	AW	AW	AW
	1	4.20	5.30	8.65	18.50
	2	4.10	5.40	8.60	18.50
T_t	3	4.30	5.20	8.70	18.00
	4	4.20	5.30	8.50	18.50
	5	4.20	5.20	8.60	18.50
$\bar{T}$		4.20	5.30	8.60	18.50
V_d		27.95	22.20	13.62	6.35
I_t		0.405	0.402	0.268	0.49

APPENDIX NUMBER THREE - EXPERIMENTAL PROCEDURE

Measurement of wave height - A portable high speed recorder (Techni-rite Electronics Incorporated) was used to measure wave height. A 340 degree rotation of the connecting rod float mechanism gave 20 divisions on the chart recorder. Hence one division on the chart was equal to a 0.284 degree of rotation. With n divisions recorded on the chart, the total deflection of the rod was $2B = 0.284\ n$. Also by measuring the initial height of the center of the potentiometer, the initial angle A of the rod with the horizontal was calculated, and $x_1 = 31.8 \sin(A+B)$, $x_2 = 31.8 \sin(A-B)$ giving the geight of the wave as $H = (x_1 - x_2)$ centimeters.

Measurement of the wave length - The time was measured for one crest to move through a particular distance. The ratio of the distance to the time is the wave speed C. Also, the revolutions of the wave paddle drive device measured with a tachometer and hence the period T was determined. The wave length L was then calculated by the equation $L = CxT$.

The steepness ratio H/L was then calculated from the above data.

Measurement of the Wind Velocity in the Wind Tunnel - For the measurement of the wind velocity, the different instruments used were the Disa model 55D01 constant temperature anemometer, 55A80 Film probe, Disa type 55D35 RMS unit, Hickok digital systems D.C. voltmeter, and digital voltmeter 510 series. The diagram connections of those different instruments is shown in Figure 18. The probe holder was indexed by an aluminum rod which ran across the width of the wind tunnel at the center of the test section. By sliding the rod through the

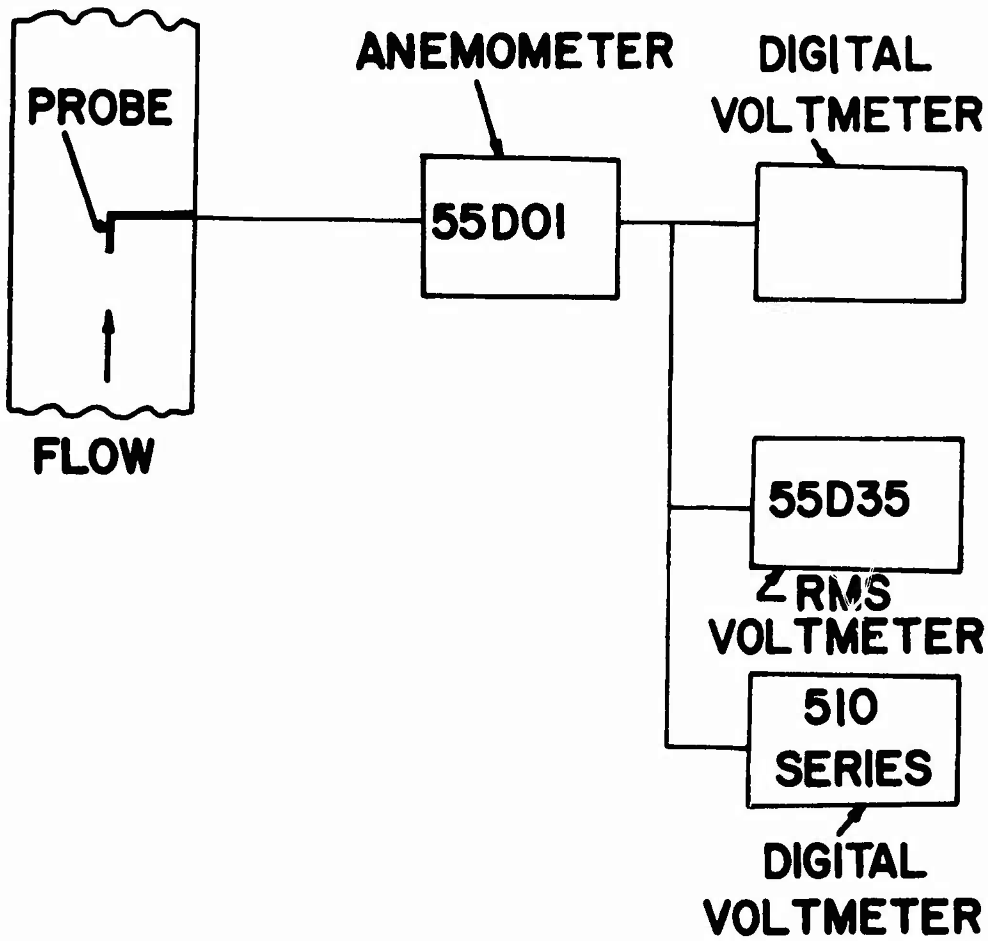

Figure 18. Diagram of the anemometer set-up.

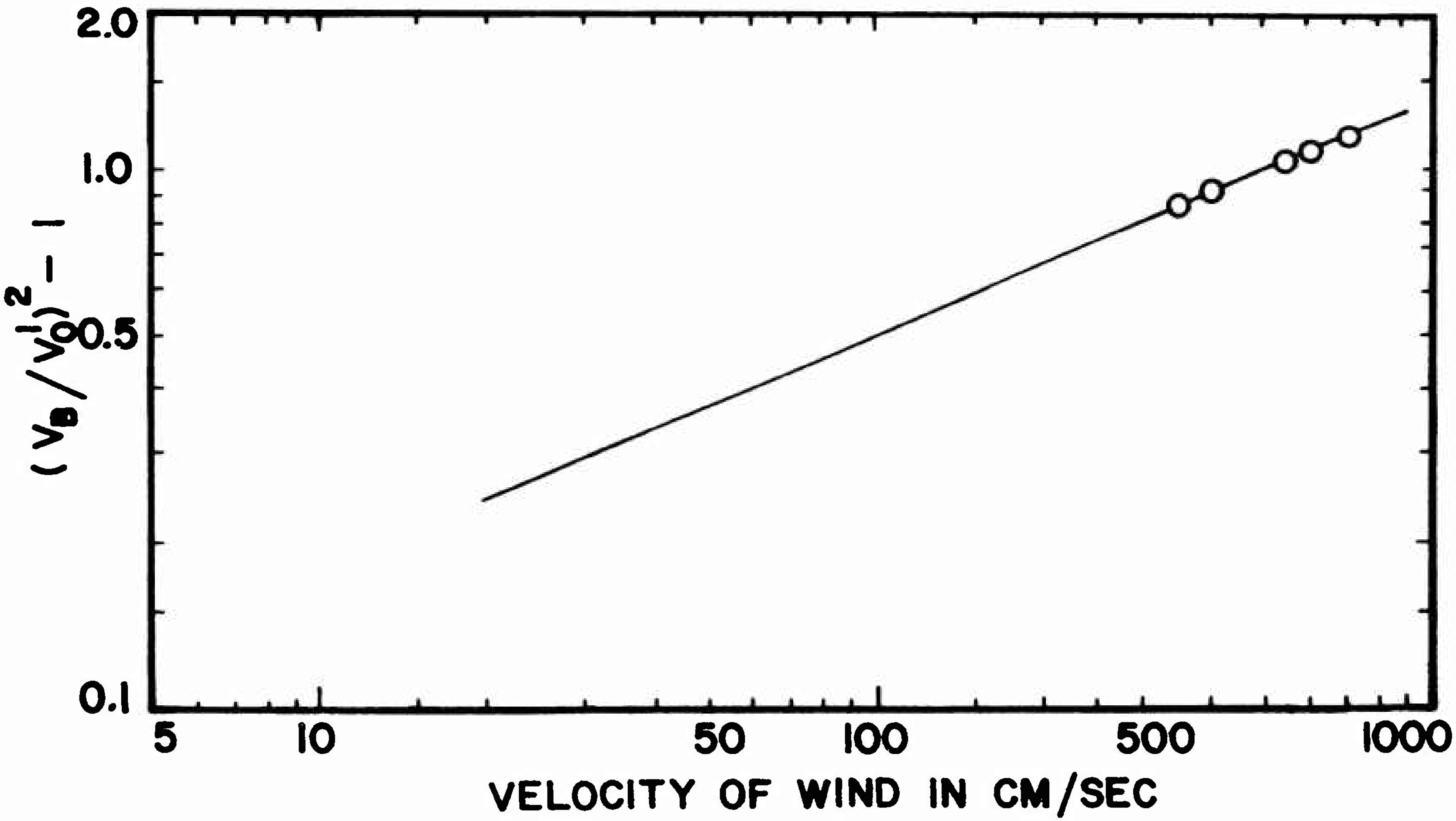

Figure 19. Calibration curve of type 55a80 hot-film probe.

wind tunnel the position of the probe could be changed along the width of the test section. Also by lowering probe holder in the rod, the vertical position of the probe could be changed in the test section.

Calibrations of the Probe - In accordance with King's law it is possible to obtain a straight-line curve inside the range of approximately 0.3 to 80 meters per second by employing a double logarithmic representation of the function $(V_B/V_o)^2 - 1$ vs. $\bar{V}$ and by proper choice of V'_o. Where V_B is the reading of digital D.C. voltmeter, $\bar{V}$ is wind velocity and $V'_o = 0.86V_o$ for a type 55A80 hot-film probe. V_o is the digital voltmeter reading with no air flow. V'_o can also be read from the plot of V^2_B vs. $\bar{V}^{0.46}$. This plot is a straight line and the intersection of this line and V^2_B axis will give a value of V'^2_o.

In the experiment the probe was calibrated at high wind velocities using a pitot tube. For five different velocities, the digital D.C. voltmeter readings V_B were taken and corresponding values of velocities $\bar{V}$ were measured with the help of a pitot tube and $(V_B/V'_o)^2 - 1$ vs. $\bar{V}$ were plotted on a double logarithmic scale. Figure 19 shows calibrations for a type 55A80 hot-film probe.

During the experiment values of V_B were noted from the digital D.C. voltmeter. Knowing the value of V'_o, the values of wind velocities $\bar{V}$ were read directly from the calibration curve.

Measurement of the Drift Velocity - With the water in the tank being quiescent, a flexible plastic float was carefully placed on the surface of the water about 1.30 meters upstream from the test section. The fan was then turned on. The float

then was timed with a stopwatch as it traveled through the 1.2 meters long test section. This terminated the run for the wind only. For waves only the float was placed on the surface of the water at the same place and the wave generator was turned on. The first few waves brought the float into the test section. The float was then timed with the stopwatch as it traveled through the test section, 1.2 meters long. For the data with waves plus wind, the same procedure was repeated, turning both the wave generator and fan on immediately after placing the float on the water surface. During the run, readings from the digital D.C. voltmeter and RMS voltmeter were taken in order to calculate wind velocity and turbulence intensity. The 1.3 meters distance mentioned above assures that the waves are uniform by the time the float enters the test section. As reported by Pottinger (1972) [33], this conclusion was reached by examining photographs of the wave which contained chalk dust particles.

By turning the wave generator off between runs and allowing the surface to become quiescent, two adverse conditions were reduced. First, the back flow currents that were reported by Mitchim (1940) [34], Russel and Osorio (1957) [35] were not observable in the test section. This conclusion was reached by Pottinger (1972) [33] after studying numerous time exposure photographs of chalk dust particles sprinkled in the water. The study of these photographs indicated that the undesirable backflow currents developed in the tank only after the wave generator had been running for approximately 7 minutes. In this experiment, the wave generator was never on for more than 3 minutes during any data run so the backflow did not develop.

Measurement of the Turbulence Intensity - The turbulence intensity I_t was calculated by the following formula:

$$I_t = \frac{V_T}{V_B} \cdot \frac{2}{n} \cdot \frac{V_B^{\,2}}{V_B^2 - V_o'^{\,2}}$$

where V_T is RMS voltmeter reading, n is defined from the equation $V_B^{\,2} = V_o'^{\,2} + k\bar{V}^{\,n}$ and $n = 0.46$. V_B, V'_o and $\bar{V}$ are the same as defined previously.